

TECHNICAL MEMORANDUMS  
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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No. 247

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METHODS OF EXPERIMENTATION WITH MODELS AND  
UTILIZATION OF RESULTS.  
By Lieut. Col. Robert.

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February, 1924.

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UTILIZATION OF RESULTS.\*

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In a report presented to the First International Congress of Aerial Navigation at Paris in 1921, we endeavored to give a general idea of the matter of testing small models in a wind tunnel and of the methods employed for rendering the results constant, accurate and comparable with one another.

We called attention to the principal causes of error which

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\* Paper read before the International Air Congress, London, 1923.

might impair the results, but gave hardly any precise data, save on the effect of the supports. Other points needed, however, to be further elucidated. Lastly, we described briefly the seemingly best method for utilizing the results of the tests made on small models in the calculation of aircraft.

The present report treats the same general subject. It gives a few corrections and a few additional details on points which were simply mentioned two years ago and which have been cleared up by subsequent experiments. It confirms and elaborates the methods recommended for the utilization of the results obtained from experimenting with small models. Lastly, it calls attention to the important role played by experiments in the development of theoretical formulas and the science of aerodynamics.

The detailed experimental results on the three points referred to in the report are given in three notes in the appendix.

A.- Objects of Aerodynamical Experiments. What are the objects of aerodynamical experiments? In order to answer this question, we must consider the present status of aerodynamic science, as regards what an engineer can expect of it, and its relations to aerodynamical experiments.

In the present state of aerodynamical science, it is not possible to determine, even approximately, from the geometric forms of a complex body like an airplane, the elements defining the resultant of the actions of the air on this body.

For a body of simple geometric shape or for special airfoil sections with parallel flow, we may apply the theorem of Kutta-Joukowski and obtain a theoretical expression for the lift. The value thus found will differ, however, by 20 to 25% from the values given by experiments. Moreover, the drag in the direction of flight cannot be calculated, but only that part of this drag due to the forces of inertia may be expressed by a theoretical formula and here again only in individual cases of simple hypotheses.

For the majority of bodies where the flow is not parallel, we cannot calculate the circulation and, consequently, we cannot even apply the formula of Kutta-Joukowski.

We must, therefore, acknowledge that theory alone is not yet capable of furnishing results sufficiently general and accurate for the designer to make his plans without recourse to direct experiments. It is nevertheless a great help and some purely theoretical formulas have been found in very good accord with experiments.

For example, if we wish to determine the position of the center of lift on a biconvex surface with a plane of symmetry, the theory indicates that this point will occupy a fixed position one-fourth the length of the chord from the leading edge, which is the precise result obtained in recent determinations made with a good degree of accuracy on more than ten biconvex wings.

Such cases are exceptional, however, and, in general, the theory can be applied only in connection with experiments. In this way, it has already furnished valuable information.

In this connection we may cite certain formulas of Prandtl and Munk, which are the result of a combination of theory and practice, but for which it is necessary to adopt simplifying hypotheses which agree only approximately with actual physical phenomena. Such formulas can be of great help to designers and it is very important to know which ones may be used with confidence and the degree of accuracy they will give.

For this purpose, a large number of experiments have been performed in France during the last two years. Several results furnished by the theory have thus been found to be applicable by the engineer. Farther along we will give, for the sake of illustration, a resume of the two investigations of this character: one, on the experimental verification of theoretical formulas enabling the calculation of a biplane from the aerodynamic data of a single wing of uniform cross-section; the other, relative to the constancy of the coefficient of the wing-section drag of a wing of varying aspect ratio and chord.

Such experimental verifications show what theoretical results are utilizable by technicians. They also have another object, more remote, perhaps, but certainly more important, namely, progress in theoretical aerodynamics. This science, like all sciences in their beginning, must employ the deductive method. The scientist must, therefore, continually create hypotheses,

which, however, will lead to progress only when capable of experimental verification, so that they may be modified or rejected, if found inaccurate.

In short, the most important object of experimental aerodynamics is to determine the value of the formulas and the degree of accuracy of results obtained by theory. This will enable the engineer to know what formulas he can use and the scientist to learn the value of the hypotheses he has originated.

Thus supported by experience, the science of aerodynamics will be able to progress and we may expect it to reach such a stage that engineers can use its formulas without continual recourse to direct experimentation. Since this is not yet the case, we must still rely on experiments alone to inform us concerning the aerodynamic properties of a wing, propeller, or airplane. This will be, therefore, the second object of experimental aerodynamics.

B.- Value of Experimentation Methods. In order to attain either of these two objects, the first and essential condition is the improvement of the methods of experimentation.

It is necessary to define accurately the conditions for the experiments, to determine the errors, eliminate the causes for the errors which follow no apparent law and establish correction formulas for the others. In this manner it is possible to obtain results which do not depend on the peculiarities of each wind tunnel and which can be reproduced with reference to per-

fectly determined experimental conditions.

The need of improving the experimental conditions became imperative in 1921, when the S.T.Ae. (Service Technique Aeronautique) with two laboratories (the Eiffel laboratory at Auteuil and the Aerotechnic Institute at Saint Cyr), had to compare the results obtained in these two laboratories with each other and also with the results obtained in other European laboratories.

The lack of agreement of the results was manifest and no comparison was possible between the various wing sections or airplane models. Moreover, it was useless to try to compare the coefficients obtained by testing models with those given by flight tests.

A methodical study of the question renders it possible to determine successively the principal causes of disagreement, namely:

1. Reaction of supports on models;
2. Slight variations in the direction of the air current with reference to the axis of the wind tunnel;
3. Nature of air flow near the model, free or obstructed by walls;
4. Variations, in certain cases, in the drag due to the supports.

The following expedients were then adopted for eliminating causes of error. All supports attached to the top (extrados) of the wings, in a region of negative pressure, were completely eliminated, as causing too great interference, which varied without definite law for different wing sections. It was found, how-

ever, that small rigid rods of sufficient length had only an insignificant influence (of the order of magnitude of errors in reading), when attached to the bottom (intrados) of the wing, the effect being the same as that of suspension by wires. These two suspension methods have therefore been adopted, to the exclusion of all others.

The angle between the axis of the wind tunnel and the direction of flow was carefully determined several times during the course of the tests. Its value was therefore known in each experiment and the angles of attack, as read, were correspondingly corrected.

The new disposition of the experiment chamber in the Saint Cyr laboratory renders it possible to experiment with the same model, without disturbing it, both in a free airstream and in one enclosed between walls. It has thus been possible to test the accuracy of a correction formula indicated by Prandtl and which led to the value of standard coefficients obtained in an unlimited airstream.

Lastly, it was found that the adjustment for the drag due to the supports had to be frequently corrected and that for very accurate experiments, in the case of suspension by wires, it had to be made before each test. A correction had to be made also for the elastic elongation of the wires.

Among the difficulties encountered in the course of these adjustments, one of them is sufficiently instructive to be mentioned here. When the model was suspended by wires, an adjust-



ment curve was established, which gave the drag  $R$  of the supporting wires in terms of the velocity. Then, in order to obtain the drag  $R$  of a model, there was subtracted from the total drag  $R$ , indicated by the balance, the value of  $R$  corresponding to the velocity of the test. With the dimensions of the current models and with wires of 0.5 mm (.02 in.) diameter, the drag  $R$  was 2 to 3 times the  $R$  of the model. It may be noted in passing that this high value of the corrective term  $R$  is a serious disadvantage of the wire suspension, otherwise very advantageous, as reducing to a minimum the interactions between the supports and the model.

After a series of tests had been executed on a wing model in May, 1922, it became necessary, for special reasons, to repeat them a month later, when the drag of the model was found to be 15% less than during the first tests. The tests were repeated several times with all possible precautions, but always gave the same result. The difference was too great to be attributed to experimental errors, so that, after further fruitless tests, the drag of the wires (which had remained the same in the two series of tests) was again determined and it was noted with astonishment that this drag had diminished about 5%, which accounted perfectly for the 15% diminution in the drag of the model.

This diminution in the drag of the wires was due to the fact that (after having been perfectly polished when installed) they had become slightly corroded in the interval between the

two tests. This result conforms, moreover, to the theory that the air filaments separate less readily from the walls of a cylinder when rough than when they are smooth and that, consequently, the negative pressure behind the cylinder is less in the former case.

The fact that steel wires offer less resistance to an air current when rusty than when perfectly polished, although logical, created a difficulty in the tests and halted the experimenters for a time.

This illustration shows what extreme care must be exercised in aerodynamical experiments. By observing the precautions and applying the corrections indicated above, results were obtained in both S.T.Ae. laboratories, which were perfectly comparable, constant and under definite experimental conditions.

C.- Utilization of Results Obtained with Models. The experimentation methods having been thus improved as much as possible, the first object of experimental aerodynamics could be attained, i.e., the possibility of testing the accuracy of theoretical formulas.

We must now endeavor to determine the conditions under which the results obtained with small models apply with sufficient approximation to full-sized airplanes.

We must proceed in such a way that Reynolds number or, more simply,  $Vl$  will have the same value for both airplane and model, which cannot be the case in our wind tunnels. Let the number

$E = Vl$  be expressed by the product of the velocity  $V$  in meters per second and the wing chord in millimeters. We generally test wings or models with an aspect ratio of 5 or 6, which gives, in tunnels of 2 meters diameter (6.56 ft.) a mean wing chord of 150 mm (5.9 in.) and

$$E = 3000 \text{ for } V = 20 \text{ m/s (65.6 ft/sec.)}$$

$$E = 4500 \quad " \quad V = 30 \quad " \quad (98.4 \quad " \quad )$$

$$E = 6500 \quad " \quad V = 45 \quad " \quad (147.6 \quad " \quad )$$

For a full-sized airplane,  $V$  is about 100,000. Systematic wind tunnel experiments, as likewise several comparisons which it has been possible to make under favorable conditions with large-surface tests on a moving car, have shown that the coefficients vary but little above a certain value of  $Vl$  which it is possible to attain. This fortunate circumstance adds greatly to the value of wind tunnel tests.

We may summarize the conclusions as follows:

Laboratory results in which  $Vl$  is less than 2000, apply but little or not at all to real airplanes;

Results in which  $Vl$  is about 3000 are applicable with errors of the order of magnitude of 6 to 8%;

Results in which  $Vl$  exceeds 6000 contain errors of less than 5% and those in which  $Vl$  exceeds 12000 may be considered practically exact;

With wind tunnels of two meters diameter, it is therefore necessary to operate at velocities exceeding 20 m/s (65.6 ft/sec.).

In an existing wind tunnel where the velocity is given, it is possible to increase the value of  $V_l$  by changing the dimensions of the model. Tests, the details of which are given at the end of this article, have shown that the drag coefficients of similar models with different chords were the same when the models were tested at the same  $V_l$ . Hence, we may experiment in a wind tunnel of 2 meters (6.56 ft.) diameter, for example, with wing models of  $60 \times 20$  cm ( $23.61 \times 7.87$  in.) instead of models  $90 \times 15$  cm ( $35.4 \times 5.9$  in.). Since the area is practically the same in the two cases, the effect of the walls will not be increased. Moreover, the drag coefficients of the wing section being the same, we may apply the known formulas rendering it possible to pass from the aspect ratio 3 to the aspect ratio 6 (formulas which give only the variation of the induced drag with the aspect ratio). If the velocity of the tunnel is 25 m/s (82 ft/sec.), we thus pass from  $V_l = 3750$  to  $V_l = 5000$ . This increase of  $V_l$ , between 3000 and 6000 is very important.

The large wind tunnel just finished by the S.T.Ae. renders it possible to obtain an air flow of 80 m/s (262.5 ft/sec.) and of 3 m (9.84 ft.) diameter. In the current tests at 60 m/s (196.8 ft/sec.) with a model of 30 cm (11.81 in.) chord, we obtain a value of  $V_l = 18000$ , which is an excellent experimental condition.

In operating thus at values of  $V_l$  greater than 6000 and even 12000, Reynolds number will be practically satisfied for both the model and the airplane, but it will not be for small



accessories, like cables, brace wires and struts. For these parts the  $V_l$  on the model will be too small (100 to 300) and the individual drag coefficients will be 4 or 5 times as large as for the corresponding airplane parts. It is therefore necessary to eliminate them as far as possible from the models, which will result in conducting the tests in the following manner:

1) Make separate models of the fuselage (without projecting accessories, such as machine guns, hoods, wind-shields and radiators attached to the fuselage; wings; horizontal and vertical tail surfaces; engines and other large parts when detachable from the fuselage.

2) Eliminate all stays and wires. Retain but one pair of struts in the middle of each half-cell, if necessary to secure rigidity. Make these struts with a rectangular cross-section, for example,  $3 \times 10$  mm ( $.12 \times .40$  in.). It is better not to use streamlined struts, because their manufacture on so small a scale is necessarily faulty and the corresponding coefficient is not accurately known. On the contrary, with struts of rectangular cross-section, the unit coefficient of drag is well defined and it is determined as well for a separate strut as for a pair of struts with one of them located a given distance behind the other.

3) The laboratory must give the coefficients  $C_x$ ,  $C_y$ , and  $C_m$ , after having deducted the drag of the uprights themselves from the experimental data.

4) The office of research must apply the law of geometric similitude, while conserving the above coefficients and must add the drag for the parts omitted from the model. For this purpose, the parts must be tested, either full-size or half-size, in the wind tunnel.

While proceeding thus, there remain, as causes of error, the interactions of the suppressed parts on the cell and fuselage, interactions which have been neglected.

It would, therefore, be necessary to know the amount of these errors for the application of the above method to be entirely correct. Some researches have already been undertaken in this connection, but the results are still incomplete and in some instances do not agree very well. This is due to the fact that the determination of these interactions is generally a difficult experimental process.

We have made some tests relating to the interactions of struts with the cell, first on small models in a wind tunnel and then on a full-sized cell on the dynamometric car at Saint Cyr. In both series of tests, the struts slightly diminished the lift (about 5%), but while the wind tunnel tests did not reveal the influence of the coefficients  $C_x$  of the wings, those performed on the car showed a corresponding diminution of these coefficients. The question, therefore, is yet to be settled.

A methodical investigation has likewise been undertaken for verifying the interactions produced on a biplane by each wing on the other, as well as the part taken separately by the upper and

lower wings in the total drag and lift. A few experiments had previously been made in this connection, but it seemed best to resume them and subject the results to the above-mentioned corrections, while operating at a velocity of 40 m/s (131.2 ft/sec.) on moderately thick wings. The principal results are given in Fig. 1.

The several conclusions may be briefly summarized as follows:

1) For normal gaps, the upper wing is but slightly affected by the lower wing. The latter, on the contrary, is strongly affected by the upper wing. Its coefficient of lift may be diminished as much as 20%.

2) When the gap is diminished, the two wings react mutually on each other. When the gap is diminished to about one-tenth of the span, the lift of the upper wing is considerably reduced. Moreover, the induced drag ( $R_{u1}$ ) exerted by the upper wing (u) on the lower wing (1) is much greater than that ( $R_{1u}$ ) exerted by the lower wing on the upper wing. This result is important, because experience here clearly invalidates the data obtained from the theory according to which  $R_{u1} = R_{1u}$ .

A very important problem of interaction is also presented by the propeller, as to how its characteristics are affected by placing a fuselage either behind or in front of it; likewise, as to what effect the presence of a propeller has on the drag of a fuselage. Tests recently made in this connection at the Eiffel laboratory (See Part III of the Appendix) show that we have the right to consider (within 2 or 3% at the most) a fuselage-



The first part of the report discusses the general situation of the country and the progress of the work. It is noted that the work has been carried out in accordance with the plan and that the results are satisfactory. The second part of the report deals with the specific details of the work and the progress of the various projects. It is noted that the work has been carried out in accordance with the plan and that the results are satisfactory.

The third part of the report deals with the financial aspects of the work. It is noted that the work has been carried out in accordance with the plan and that the results are satisfactory. The fourth part of the report deals with the personnel aspects of the work. It is noted that the work has been carried out in accordance with the plan and that the results are satisfactory.

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propeller group as having the same coefficients of functioning as an isolated propeller and that, furthermore, in the evaluation of the structural drag of an airplane, it is necessary to consider the drag of the fuselage, deducted from that obtained for the model in a wind tunnel, without taking into account the effect of the propeller. This is because the increase in the fuselage drag due to the propeller and the increase in the propeller thrust tend to offset each other, so that the correction due to their resultant is very small.

It would be of great interest to verify these conclusions on an airplane in flight, which would consist in determining the torque transmitted to the propeller and the thrust exerted by the latter. Such tests have been tried many times in various countries. In particular, the S.T.Ae. in France has used an experimental airplane for this purpose. It was possible to measure the engine couple or torque, but the dynamometer interposed between the propeller and airplane for measuring the thrust has always given too large results. This is perfectly explained by the results of the above-mentioned laboratory tests showing the existence of two interior forces in the airplane-propeller system, which have no effect on the motion of the airplane, but which are recorded by the dynamometer.

This was verified on the experimental airplane. The airplane in flying position, was held by a dynamometer secured to a stake driven into the ground and, with the engine running, the indications of the recording dynamometer attached to the propeller



were compared with the indications of the dynamometer attached to the stake. The former indicated 520 kg (1146.4 lb.) and the latter only 435 kg (959 lb.)

It does not seem possible, therefore, to measure the real traction and consequently the efficiency of a propeller in flight. Hence we cannot test the legitimacy of employing the law of similitude, which, by applying to the tests of small propellers ( $d = 40$  cm), (15.7 in.) is now the only means for determining the efficiency of propellers during flight at various revolution speeds. Perhaps devices may yet be invented to enable this determination.

These few considerations on measuring the interactions of airplane parts indicate the importance of researches in this connection. The results already obtained, a few of which have just been recalled, make it probable that the above-described method is the best for utilizing the results obtained with small models.

In order to obtain accurate results by this method, it would be necessary to determine, during flight, the lift and drag coefficients of the airplane. Unfortunately such tests are particularly difficult. It is necessary to determine the propeller pull by means of the estimated power of the engine (which varies with the altitude and the carburetor adjustment) and likewise by the estimated efficiency of the propeller.. Thus an error of 5 to 10% may easily be made in the value of this traction. With present measuring instruments, an error of 3 to 4% must be assumed



in the velocity and a minimum error of 5% in the angle of attack and the inclination of the flight path to the vertical. Under these conditions, if we examine the possible error in the values of  $C_x$  and  $C_y$  deduced from the measurements made, we arrive at the conclusion that, under the best conditions, the possible error in  $C_y$  is about 8% and that in  $C_x$  about 15%.

D.- Conclusion. Considering the very great difficulty of these flight tests, it is not certain that a few accurate results can be obtained by this method on real airplanes.

A dynamometric car, like the one at the Institute of Saint Cyr, is capable of producing important results since the nearness to the ground is not the source of any appreciable error, when proper precautions are taken. Only a few such experiments can be made, however, due to the length of time consumed in preparing for them and the large expense involved.

Therefore, wind tunnel tests on small models are now the only practical means of aerodynamical research and we think that, if the proper precautions are observed, the results will be entirely satisfactory. They will surely constitute an accurate means for controlling theoretical researches and a valuable guide to assist them in their progress.

They will be utilisable in engineering projects, with an allowable error, under the express reservation that the product  $Vl$  in testing the model shall have a sufficient value (3000 minimum, 6000 or more for accurate results). The latter value can

be attained for the principal parts of an airplane, such as the wings and fuselage, but not for the accessories. We cannot, therefore, apply to the whole the law of geometric similitude. We must proceed differently for the two classes of parts, as already indicated. The interactions will, therefore, continue to be sources of error.

A knowledge of the values of these interactions in the various cases is accordingly essential. Researches have already been begun in this connection.

Furthermore, new and little known domains, like that of soaring flight, which will require tests of a very special nature, yet remain to be explored.

These researches, in particular, may hold surprises, since the laws governing the flow of fluids, and especially those which apply to the air, are yet very imperfectly known.

Experimental aerodynamics still has before it a magnificent field to be explored.

A P P E N D I X.

Part I - Biplanes: Verification of Theoretical Formulas  
and Determination of Interactions.

Object of Tests.- These tests were undertaken for the purpose of verifying the accuracy of formulas deduced from the vortex theory for the calculation of biplane cells. In this connection, it is known that the experiments executed by Munk agreed fairly well with the theoretical formulas. They were executed, however, at a low speed ( $10 \text{ m/s} = 32.8 \text{ ft/sec.}$ ) and with relatively thin wings. We intend to continue these experiments at a high velocity ( $40 \text{ m/s} = 131.2 \text{ ft/sec.}$ ) on moderately thick wings of the Joukowski type of cross-section.

Experimental Means Employed.- The tests were made by Toussaint at the Aerodynamic Institute of Saint Cyr. He used wind tunnel No.1 of two meters diameter with a velocity of  $40 \text{ m/s}$  ( $131.2 \text{ ft/sec.}$ ) and, as constituting the biplane cell, two wing models of like dimensions and cross-section, namely: span 708 mm (27.9 in.) chord 118 mm (4.65 in.) aspect ratio 6, area  $0.083 \text{ sq.m}$  ( $.89 \text{ sq.ft.}$ ), models SC 56a and SC 56c. Model No.56c was used constantly as the wing acted upon and was attached in the customary position to the wire balance. Model 56a was used as the wing causing the interaction and was attached to a fixed but adjustable support. It was sometimes placed above and sometimes below



the wing acted upon. For each of these two positions, the gap was varied and for each gap the angles of both wings were varied from  $\pm 9^\circ$  to  $\pm 15^\circ$ . Furthermore, for each gap and for each angle of attack of the wing producing the interaction, the angle of the wing acted upon was varied  $\pm 1^\circ$  and  $\pm 2^\circ$ . In the first series of tests, account was taken only of the tests relating to the variation of the gap, without interinclination. Lastly, the adjustment of the angles of attack was made in such manner that, for each one of them, the biplane remained erect, i.e., so that the leading and trailing edges of the two wings remained respectively in the same vertical planes.

Results Obtained.- Figure 1 gives the polar of the wing SC 56c, serving as the upper wing of the biplane and acted upon by the lower wing SC 56a, for the gaps 60 (2.36), 87.5 (3.44), 135 (5.31), and 1.87 mm (7.36 in.). Figure 2 gives the polar of wing of SC 56c, serving as the lower wing of the biplane and acted upon by the upper wing SC 56a for the same gaps as above.

Figures 3-10 give the lift and drag curves separately and also the polar curves for each biplane combination.\* For each of these combinations, the separate lift and drag curves and the polar for the whole biplane were calculated, by taking for each angle of attack the mean of the values corresponding to the lower

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\* The coefficients of  $C_x$  and  $C_y$ , used in these tests, are those of the formulas:

$$\begin{aligned}\text{Lift} &= F_y = (C_y/100)S(aV^2/2g). \\ \text{Drag} &= F_x = (C_x/100)S(aV^2/2g)\end{aligned}$$

in which  $a$  is the specific gravity of the air.

and upper wing.

By comparing with the polar of the isolated wing, we can determine from these data the quantities  $\Delta C_X/C_Y^2$  and  $\Delta \alpha/C_Y^2$  for each biplane combination.

A.-- Comparison of the experimental values with the ones derived from Prandtl's theory.

It is known that the coefficient of induced drag of a biplane composed of two like wings (with neither stagger nor decalage) is given by the formula

$$C_{XB} = C_Y^2 (S/\pi b^2) (1 + \sigma)$$

in which  $b$  is the span,

$S$ , the area of one wing,

$\sigma$ , a coefficient given in Prandtl's theory in terms of the relative gap  $G/b$ .

On comparing  $C_{XB}$ , for the biplane, with  $C_{XM}$  for the monoplane corresponding to one of the wings, we have

$$\Delta C_X/C_Y^2 = (C_{XB} - C_{XM}/C_Y^2) = (S/\pi b^2) \sigma = \sigma/\pi \lambda$$

in which  $\lambda$  is the aspect ratio. In the present instance, where  $\lambda = 6$ , we have

$$1) \quad \Delta C_X/C_Y^2 = \sigma/18.84$$

Similarly, for the angle of attack  $\alpha$ , we have

$$2) \quad \Delta \alpha/C_Y = \sigma/18.84 \times 57.3,$$

$\alpha$  being expressed in degrees. These formulas (1 and 2) enable

the experimental determination of  $\sigma$  and  $\Delta\alpha/C_y$ .

Thus we obtain the following table.

Relative gap G/b	$\sigma$		$\Delta\alpha/C_y$		e
	Theory	Practice	Theory	Practice	
0.264	0.406	0.325	1.23°	1.17°	1.4%
0.191	0.497	0.443	1.51°	1.55°	0.7%
0.123	0.608	0.641	1.85°	3.6° - 0.6°/C <sub>y</sub>	0.2%
0.084	0.687	0.690*	2.09°	3.65° *	0.0%

When  $C_{xB}$  is calculated by starting from  $C_{xM}$  and using the theoretical value of  $\sigma$ , the relative error  $e$  committed in  $C_{xB}$  for  $C_y = 1$  (which is the maximum practical value) is the one given in the last column. It is obvious that this error does not reach 1.5%, which is very satisfactory.

#### B.- Influence of decalage.

For each of the above gaps, decalages of  $\pm 1^\circ$  and  $\pm 2^\circ$  were given the wings. The polars and separate lift and drag curves being plotted as above, the experimental polar of the biplane was compared with the theoretical polar. The results for  $\Delta C_x/C_y^2$  are given in the following table.

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\* Approximate mean.

Values of $\Delta C_x/C_y^2$				
Real gap G	$\left\{ \begin{array}{l} 2.36 \text{ in.} \\ 60 \text{ mm} \end{array} \right.$	$\left\{ \begin{array}{l} 3.44 \text{ in.} \\ 87.5 \text{ mm} \end{array} \right.$	$\left\{ \begin{array}{l} 5.31 \text{ in.} \\ 135 \text{ mm} \end{array} \right.$	$\left\{ \begin{array}{l} 7.36 \text{ in.} \\ 187 \text{ mm} \end{array} \right.$
Relative gap b/G	11.8	8.10	5.25	3.78
Decalage $0^\circ$	0.0364	0.0340	0.0250	0.0170
" $\pm 1^\circ$	0.0340	0.0330	0.0250	0.0186
" $-1^\circ$	0.0355	0.0330	0.0253	0.0178
" $\pm 2^\circ$	0.0360	0.0345	0.0235	0.0190
" $-2^\circ$	0.0340	0.0330	0.0235	0.0195

It follows from these numerical values that the effect of the decalage (up to  $\pm 2^\circ$ ) on the induced drag is very small. On closer examination, it is observed that the positive or negative decalage is rather unfavorable in the case of gap 187 mm (7.36 in.) ( $\Delta C_x/C_y^2$ ) being the least for a gap of  $0^\circ$ , and that the decalage has almost no effect with a gap of 135 mm (5.31 in.).

Lastly, for smaller gaps of 87.5 (3.44) and 60 mm (2.36 in.) a negative decalage seems to decrease the induced drag slightly, while a positive decalage seems to increase it slightly.

The notion of an induced angle likewise appears to be confirmed in the sense that  $\Delta \alpha$  is usually a linear function of  $C_y$ , but the representative straight line does not generally pass through the origin.

#### C.- Mutual interaction of the two wings.

The examination of the curves in Figs. 1-10, lead to the following general considerations.

1) Gaps  $G/b = .26$  and  $.20$

The  $C_y$  of the upper wing influenced by the lower wing are the same as for an isolated wing. The  $C_y$  of the lower wing influenced by the upper wing are 15% below those of an isolated wing. From the viewpoint of  $\Delta C_x$ , the influence of the upper wing on the lower is the same as that of the lower wing on the upper. In both cases the  $\Delta C_x$  with relation to an isolated wing is the same, namely, constant and practically equal to 0.006. For the gap of 20%, a difference appeared between the mutual influences in the vicinity of zero angle of lift.

2) Gaps  $G/b = .12$  and  $.08$

The  $C_y$  of the influenced upper wing are smaller than those of an isolated wing

by 10% for  $C_y = 0.5$  and  $G/b = .12$

by 40% for  $C_y = 0.5$  and  $G/b = .08$

The  $C_y$  of the influenced lower wing are sometimes larger and sometimes smaller than those of an isolated wing. The interactions on the  $C_x$  are not the same for both wings (contrary to a lemma of Munk). The  $\Delta C_x$  are very different for the two wings.

Starting with the polars of each component wing of the biplane, it is possible to calculate for any given  $C_y$  the increments  $\Delta C_{x1}$  and  $\Delta C_{xu}$  to give to the  $C_x$  of the isolated wing, in order to find the polar of each component wing of the biplane. Toussaint was able to represent these increments by formulas of the form

$$\Delta C_{x1} = \lambda_1 + \mu_1 C_y^2$$

$$\Delta C_{xu} = \lambda_u + \mu_u C_y^2$$

in which the coefficients  $\lambda_1$ ,  $\mu_1$ ,  $\lambda_u$  and  $\mu_u$  may be represented by curves in terms of  $G/b$ . If, therefore, we wish to calculate each wing separately, starting with the primitive monoplane, we cannot use theoretical formulas, but must resort to the above formulas with the experimental determination of the coefficients.

## Part II - Constant of Drag for Wing Sections of Various Chords.

(Experiments performed by A. Lapresle at the Eiffel Laboratory.)

1.- Object of the Tests.- The object of these tests was to find whether the drag coefficients of similar wing models, but of different areas and aspect ratios, were always the same when said models were tested at the same  $V_l$ .

2.- Method of Testing.- For a given lift, the wing-section drag is the difference between the total drag and the induced drag. For comparing wing-section drags of wings of different areas it is, however, necessary to correct the total drag for a small error due to the effect of the boundaries of the air stream and which, for a stream of a given diameter varies according to the area of the surface tested. At the Auteuil laboratory, where the air stream passes freely through the chamber, this correction must be deducted from the total drag. It is useful to note the numerical importance of such a correction.

3.- Importance of the Correction Due to the Effect of the Boundary Walls of the Air Stream.- Let  $F_x$  and  $F_y$  represent the drag and the lift of a wing expressed by the formulas  $F_x = K_x S V^2$  and  $F_y = K_y S V^2$ . The coefficient of induced drag  $K_{xi}$  for a model of span  $b$  and chord  $c$  is

$$K_{xi} = (16/\pi) (c/b) K_y^2 = 5.10 (c/b) K_y^2.$$

The correction due to the air stream boundaries, for a tunnel of two meters diameter, is  $\Delta K_x = 0.644 K_y^2 c b$ . The ratio  $\Delta K_x / K_{xi}$  is independent of the lift and of the velocity  $V$ , but depends directly on the span and is  $0.126 b^2$  for the Eiffel wind tunnel. For a model with a mean span of 90 cm (35.4 in.) it is obvious that  $\Delta K_x$  is of the order of magnitude of  $1/10 K_{xi}$ , so that it is necessary to make the correction for the wall.

4.- Surfaces Tested.- We have had occasion to test two kinds of wing sections of which we possess models of different sizes. They are shown on Fig. 11.

The first is the Göttingen wing section No. 430, of which we have tested two models, one measuring  $1000 \times 200$  mm ( $39.37 \times 7.87$  in.) (aspect ratio 5), and the other  $708 \times 118$  mm ( $27.9 \times 4.65$  in.) (aspect ratio 6). Their surface areas were respectively  $0.2$  ( $2.15$ ) and  $0.083$  m<sup>2</sup> ( $.89$  sq.ft.), thus being in the ratio of  $2.4 : 1$ . The wing with the longer chord was made the object of a special test at  $15$  m/s ( $49.2$  ft./sec.), so that  $V_l$  was practically the same for both wings (about 3000).

The second wing section, Besson (E 352), was represented by

two models of like span (300 mm = 31.5 in.) and different chords (145 (5.71) and 290 mm (11.42 in.)). Their aspect ratios therefore differed greatly, being 5.5 and 2.75 in the ratio of 1 : 2.

The same as for the preceding wing section, the tests were made at velocities giving the same  $V_l$  for both sections. The velocity was 28 m/s (91.9 ft/sec.) for the section with the shorter chord and 14 m/s (45.9 ft/sec.) for the other.

5.- Results of the Tests.- In Fig. 11 the drag coefficients  $K_x$  are plotted against the lift coefficients  $K_y$ . It is seen that the two curves are very near each other for each of the two wing sections tested, the agreement being particularly striking for the wings having the cross-section E 356. The agreement is not so good for the two wings having the cross-section E 352, though remaining satisfactory up to  $K_y = 0.04$ , i.e., in all the regions of the polar utilized in normal flight.

Above  $K_y = 0.04$  the curves diverge considerably. This may be due to the fact that the wing 800 × 290 mm has too long a chord for our entrance cone, but it may be due also to the small aspect ratio (2.75) of one of the wings, which renders a little uncertain the evaluation of the induced drag for relatively high lifts.

In short, these tests demonstrate that, in a laboratory like the one at Auteuil, we may legitimately utilize, for comparing wing sections with one another, wings with chords not exceeding 20 cm (7.87 in.). This has the great advantage of notably in-



creasing the  $V_l$  at which we may test the wings and of enabling us to attain  $V_l$  of the order of magnitude of 6000, beyond which we know the wing-section drag coefficients are practically constant. Fig. 11 also shows, in addition to the wing-section drag curves of which we have just spoken, the same curves (dotted) for wings with longer chords tested at velocities of 24 (78.7 ft.) and 28 m/s (91.9 ft/sec.) (mean velocity, 26 m/s = 85.3 ft/sec.). We were thus able, with the wing having a chord of 290 mm, to obtain  $V_l$  of the order of magnitude of 7500 ( $26 \times 290 = 7540$ ).

It is seen that the wing-section drags thus obtained are slightly smaller than the ones obtained by our customary tests, a result which is not surprising, since the wing-section drag is produced largely by friction. All the numerical values are given in the following table.

Table.

S.T.Ae.  
Eiffel Laboratory

Drags on Similar Wing Sections with Different Chords.

Göttingen wing section 430 (E 356)

$\alpha$	$-9^\circ$	$-6^\circ$	$-3^\circ$	$0^\circ$	$3^\circ$	$6^\circ$	$9^\circ$	$12^\circ$	$15^\circ$
	Wing of $\begin{cases} 1000 \times 200 \text{ mm} \\ 39.37 \times 7.87 \text{ in.} \end{cases}$ $V = 14 \text{ m/s (45.9 ft/sec.)}$								
100 $K_y$	-0.55	0.805	2.055	3.42	4.63	5.87	6.97	7.65	7.90
100 $K_{x_t}$	0.109	0.100	0.119	0.189	0.297	0.457	0.648	0.790	1.114
100 $K_{x_i}$	0.003	0.007	0.043	0.119	0.220	0.353	0.495	0.596	0.635
100 $K_{x_p}$	0.106	0.093	0.076	0.070	0.077	0.104	0.153	0.194	0.479
	Wing of $\begin{cases} 1000 \times 200 \text{ mm} \\ 39.37 \times 7.87 \text{ in.} \end{cases}$ $V = 26 \text{ m/s (85.3 ft/sec.)}$								
100 $K_y$	-0.608	0.794	2.164	3.562	4.768	6.065	7.142	7.843	7.865
100 $K_{x_t}$	0.0935	0.0855	0.117	0.1935	0.306	0.473	0.660	0.866	1.165
100 $K_{x_i}$	0.005	0.006	0.048	0.130	0.232	0.375	0.520	0.630	0.630
100 $K_{x_p}$	0.088	0.030	0.069	0.0635	0.074	0.104	0.140	0.236	0.535
	Wing of $\begin{cases} 708 \times 118 \text{ mm} \\ 27.9 \times 4.65 \text{ in.} \end{cases}$ $V = 26 \text{ m/s (85.3 ft/sec.)}$								
100 $K_y$	-0.38	0.94	2.30	3.66	4.86	6.20	7.21	8.10	8.32
100 $K_{x_t}$	0.122	0.098	0.122	0.182	0.285	0.434	0.605	0.777	1.070
100 $K_{x_i}$	0.001	0.007	0.045	0.114	0.201	0.326	0.442	0.558	0.583
100 $K_{x_p}$	0.121	0.091	0.077	0.068	0.084	0.108	0.163	0.219	0.482

Table (Cont.)

Drags on Similar Wing Sections with Different Chords.

Gottingen wing section 430 (E 356).

$\alpha$	$-3^\circ$	$0^\circ$	$3^\circ$	$6^\circ$	$9^\circ$	$12^\circ$	$15^\circ$	$18^\circ$
		Wing of $\begin{cases} 800 \times 290 \text{ mm} \\ 31.5 \times 11.42 \text{ in.} \end{cases}$ $V = 14 \text{ m/s (45.9 ft/sec.)}$						
100 $K_y$	0.096	1.05	2.00	3.00	4.04	4.89	5.40	6.05
100 $K_{x_t}$	0.086	0.102	0.144	0.225	0.364	0.545	0.712	0.968
100 $K_{x_i}$	0.000	0.020	0.074	0.168	0.301	0.442	0.540	0.676
100 $K_{x_p}$	0.086	0.082	0.070	0.057	0.063	0.103	0.172	0.292
		Wing of $\begin{cases} 800 \times 290 \text{ mm} \\ 31.5 \times 11.42 \text{ in.} \end{cases}$ $V = 28 \text{ m/s (91.9 ft/sec.)}$						
100 $K_y$	0.061	1.00	2.04	3.04	4.04	4.80	5.50	5.89
100 $K_{x_t}$	0.085	0.0915	0.138	0.221	0.364	0.537	0.726	1.00
100 $K_{x_i}$	0	0.0185	0.077	0.171	0.302	0.427	0.574	0.642
100 $K_{x_p}$	0.085	0.073	0.061	0.050	0.062	0.110	0.152	0.358
		Wing of $\begin{cases} 800 \times 145 \text{ mm} \\ 31.5 \times 5.71 \text{ in.} \end{cases}$ $V = 28 \text{ m/s (91.9 ft/sec.)}$						
100 $K_y$	0.265	1.48	2.98	4.16	4.81	5.53	6.36	5.96
100 $K_{x_t}$	0.097	0.093	0.135	0.225	0.343	0.520	0.900	1.54
100 $K_{x_i}$	0.006	0.020	0.083	0.161	0.215	0.285	0.380	"
100 $K_{x_p}$	0.091	0.073	0.052	0.064	0.128	0.235	0.520	"

Part III - Effects of the Presence of a Fuselage  
before or behind a Propeller.

The object of the tests made at the Eiffel laboratory in 1922 was to study the functioning of a propeller mounted either before or behind a fuselage. It was not sought to determine separately the functioning coefficients of the affected propeller nor the drag coefficients of an affected fuselage, since the law of variation of these coefficients is complicated and it is impossible to apply laboratory results to cases other than those made the object of the tests. It was preferred to consider the propeller and fuselage as constituting an assembly whose functioning was being investigated. The advantage of this method is due to the fact that the effects of the interaction of the propeller and fuselage tend to offset each other, thus rendering the correction to be made for their resultant very small.

Figures 13 and 14 show the different arrangements employed during these tests. Arrangement No. 1 is the one described in the works of Mr. Eiffel. The propeller to be tested is connected with the engine by means of the vertical shaft of a bevel gear. The arm is protected by a sheath independent of the measuring instruments. Assembly No. 2 differs from the first in that the vertical shaft is surrounded by a streamlined sheath forming part of itself. Arrangement No. 3 differs from No. 2 by the interposition, behind the propeller, of a fuselage rigidly attached to the vertical arm. Arrangement No. 4 is described in

the works of Mr. Eiffel and is used in testing propellers and windmills. This device was adopted for testing propellers behind a fuselage (Fig. 15).

In Fig. 12 (arrangement 2 & 3) and Fig. 15, the measured thrust is not the effective thrust of the propeller. If  $T_t$  represents this thrust,  $D_t$  the drag of the streamlined tube in arrangement 2 or of the combination of tube and fuselage in arrangement 3. The measured thrust is then  $T_t - D_t$ .  $D_t$  may be resolved into two components: namely,  $D$  the drag when there is no interaction and  $\Delta D$  which is the unknown part of the drag due to the interaction. Hence  $D_t = D + \Delta D$ . The effective propeller thrust in the presence of the fuselage is, therefore,

$$T_e = T_t - \Delta D = (T_t - D_t) + D.$$

This is the quantity which must be introduced into the calculations, if no account is taken of the increase in the fuselage drag due to the slipstream. All the components of this quantity can be measured directly.

The efficiency is designated by the expression  $\eta = (T_e \times V / P_r)$ , in which  $T_e$  is the effective thrust,  $P_r$  the power absorbed and  $V$  the velocity.

Figure 13 gives the results of these tests. The curves of efficiency  $\eta$  and of power  $\phi$  are plotted against  $V/nD$ , the coefficient  $\phi$  being defined by  $\phi = P_r / n^3 D^5$ , in which  $n$  is the r.p.s.,  $D$  the diameter in meters and  $P_r$  the power absorbed in kilograms.

From these curves we can see how small the effect of a fuselage behind the propeller is on the curves of efficiency and power. We find a very slight increase in the maximum efficiency.

When there is a fuselage in front of the propeller, we find a slight decrease in the efficiency and a slight increase in the power coefficient, as compared with an isolated propeller.

Testing Helicopter Propellers. - Figure 15 gives the diagrams of three arrangements employed for determining the effect of a fuselage or wall near a helicopter propeller.

- A - The propeller blows against a wall or draws in the air from the side of the wall.
- B - The same tests, but with wall very near propeller.
- C - Effect of the presence of a fuselage.

The tests were made with the standard propeller of the Eiffel laboratory, with a relative pitch of 0.750, relative chord of 0.085 and a diameter of 0.905 m (35.63 in.). The rotation speed varied from 1500 to 3000 R.P.M.

Figure 15 also gives the results obtained,  $\tau$  and  $\varphi$  being the thrust and power coefficients of the propeller defined by  $\tau = T/n^2 D^4$  and  $\varphi = P_T/n^3 D^5$  in kilogram-meters per second. There is also given the Breguet "quality" defined by  $q = (\tau^{3/2})/(\varphi)$ .

#### Results of the Tests.

1. Tests 1, 2, 3, 4. These tests show that, in the two arrangements A and B, the strongest thrusts (and the strongest

"qualities") are obtained when the wall formed by the doors is on the suction side of the propeller. Thus a helicopter propeller, with a vertical axis, blowing the air toward the ground, is not assisted by the presence of the latter.

2.- Tests 5 and 6. In tests 5 and 6 the propeller is in the same position as in test No. 4, but the doors which close the entrance cone were at first opened  $90^{\circ}$  (test No. 5) and then opened clear back on the outside (test No. 6).

The results confirm the fact already mentioned, that the presence of doors on the suction side increases the coefficient of thrust. Here the increase is 5%.

Remark.- Test No. 6, in which the doors were wide open, gave the largest value of  $\varphi$  (0.0118). This test is the normal arrangement for determining the characteristics of a helicopter propeller. It is obvious that in this case we are enabled to obtain the highest coefficients  $\varphi$  and, consequently, to estimate the lifting qualities of the propeller.

3.- Tests 7 and 8. These tests were undertaken for the purpose of discovering the effect of a fuselage on a streamlined sheath surrounding the vertical shaft of the engine.

In experiment No. 7, the fuselage had been removed. The results given in Fig. 15 show that the presence of the fuselage did not appreciably affect the results of the tests.

Conclusions.- The above-described tests show that it is correct (within 2 or 3% at the most) to consider a propeller-fuselage group as having the same functioning coefficients  $\varphi$  and  $\eta$  as an isolated propeller, especially within the practical region of functioning, comprising, for driving propellers, only the speeds near the maximum efficiency.

In all the cases, it is sufficient, in determining the structural drag of an airplane, to take account of the fuselage drag, on the assumption that the latter is not affected by the propeller, which greatly simplifies the process.

The above conclusions hold good for helicopter propellers. Another point is that helicopter propellers are not assisted by the presence of the ground, against which they necessarily blow, if they are to exert any lifting force.

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National Advisory Committee  
for Aeronautics.



Fig. 1

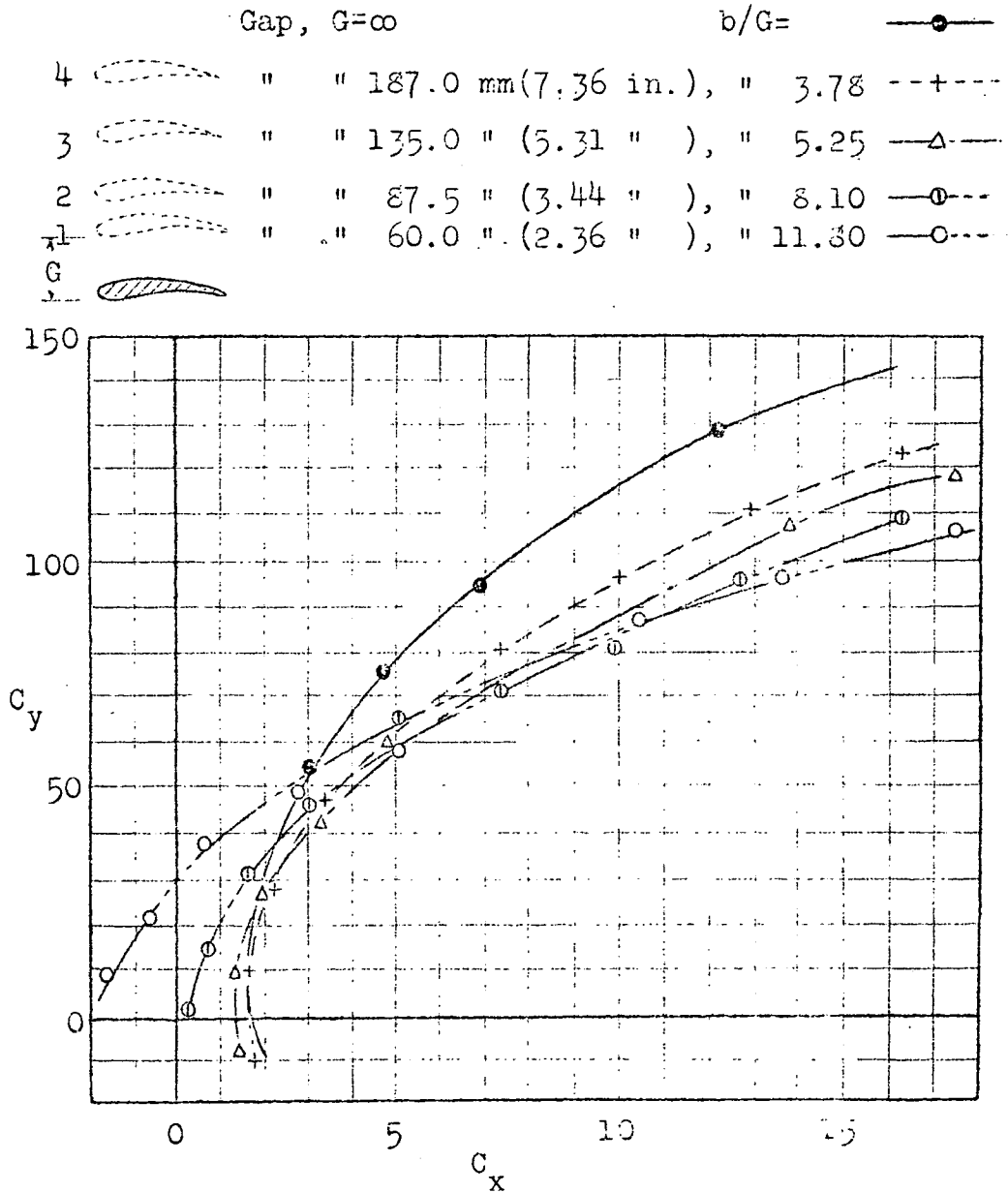


Fig. 1 Biplane S.C. 56c.a. Straight biplane without decalage. Wing S.C. 56c constituting lower wing affected by upper wing S.C. 56a.

Fig. 2

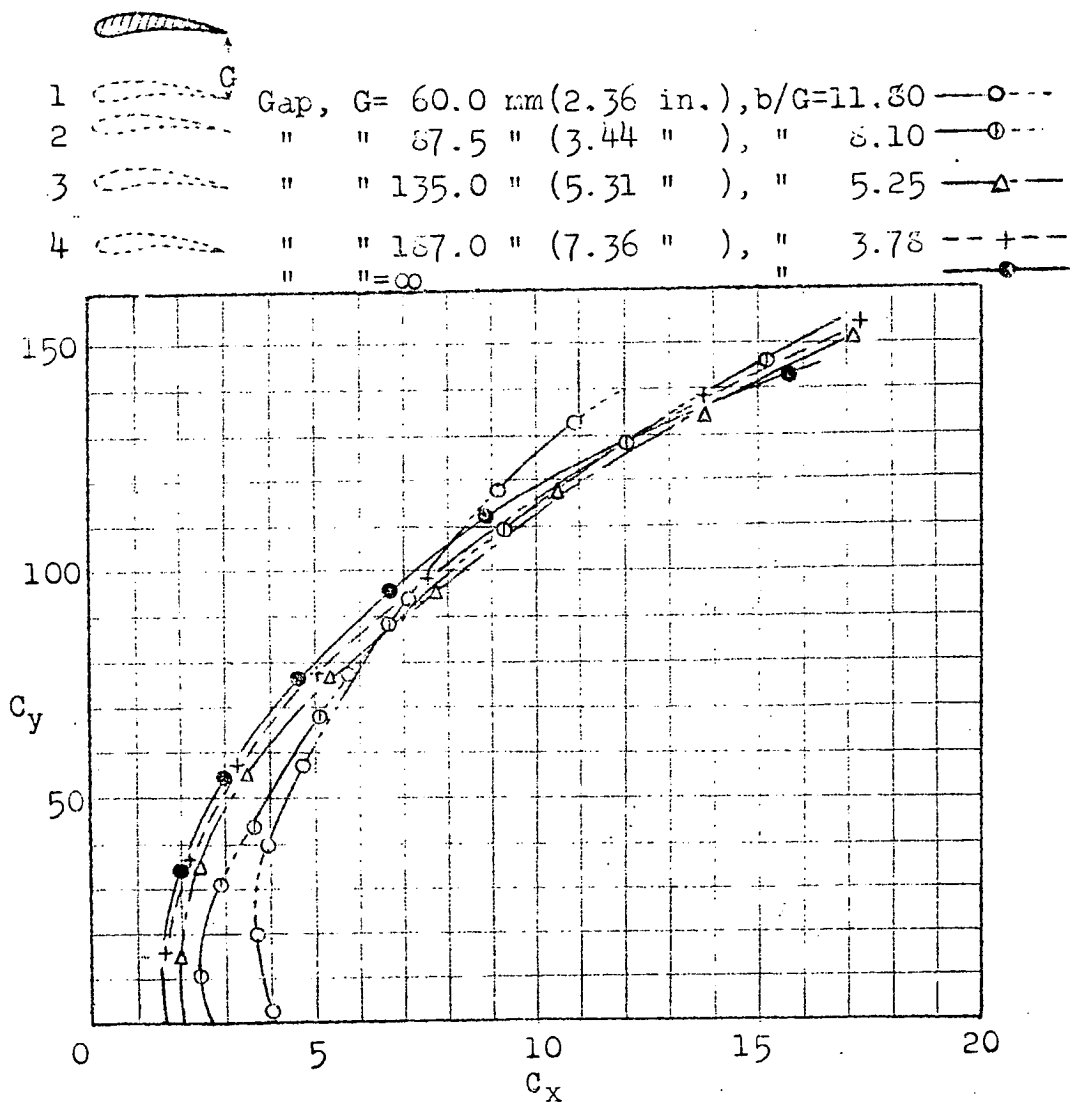


Fig. 2 Straight biplane without decalage. Upper wing S.C. 56c affected by lower wing S.C. 56a.

Fig. 3

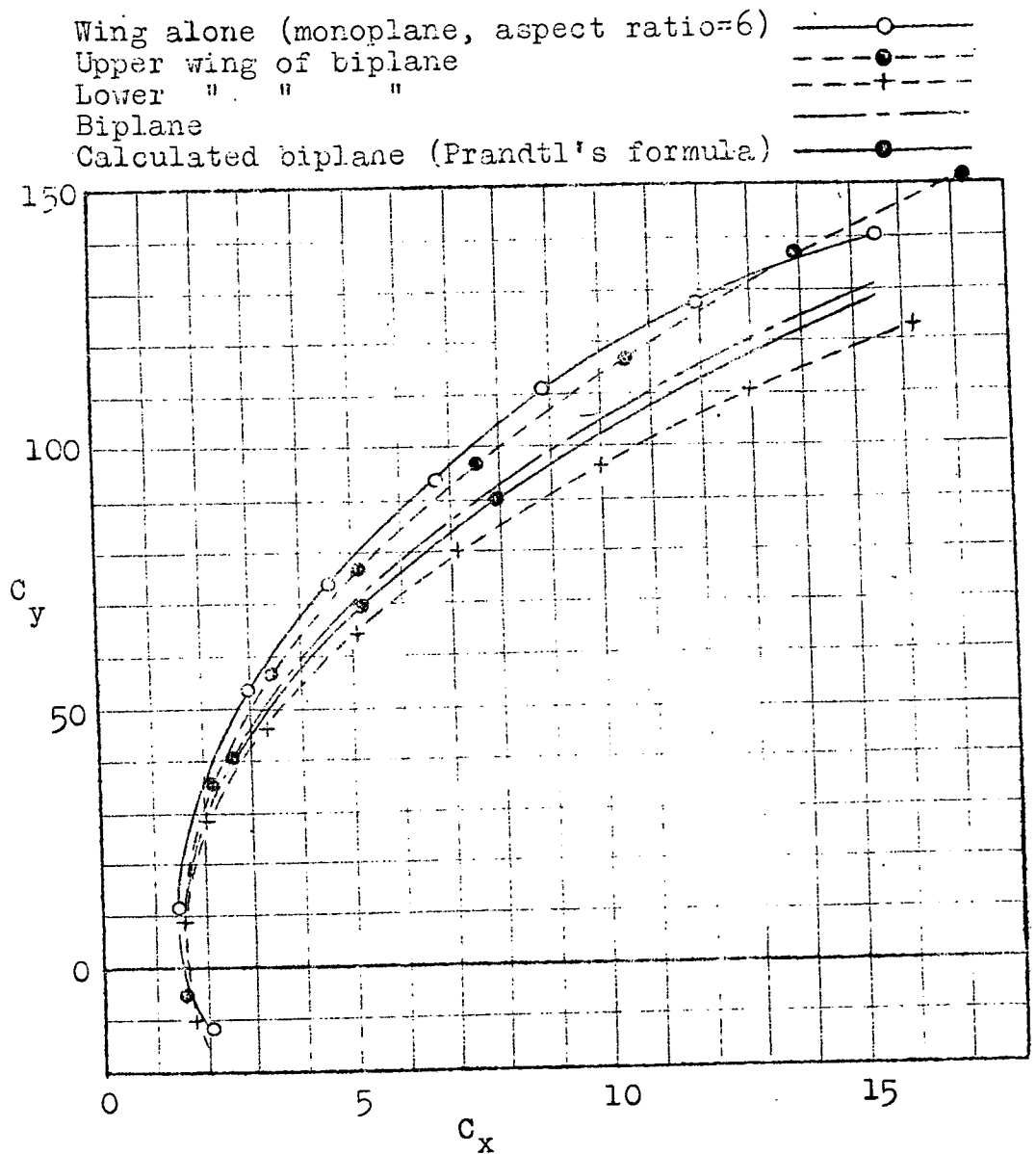


Fig. 3 Biplane S.C. 56c.a. Gap 187.0 mm (7.36 in.)  
 $b/C=3.78$

Fig. 4

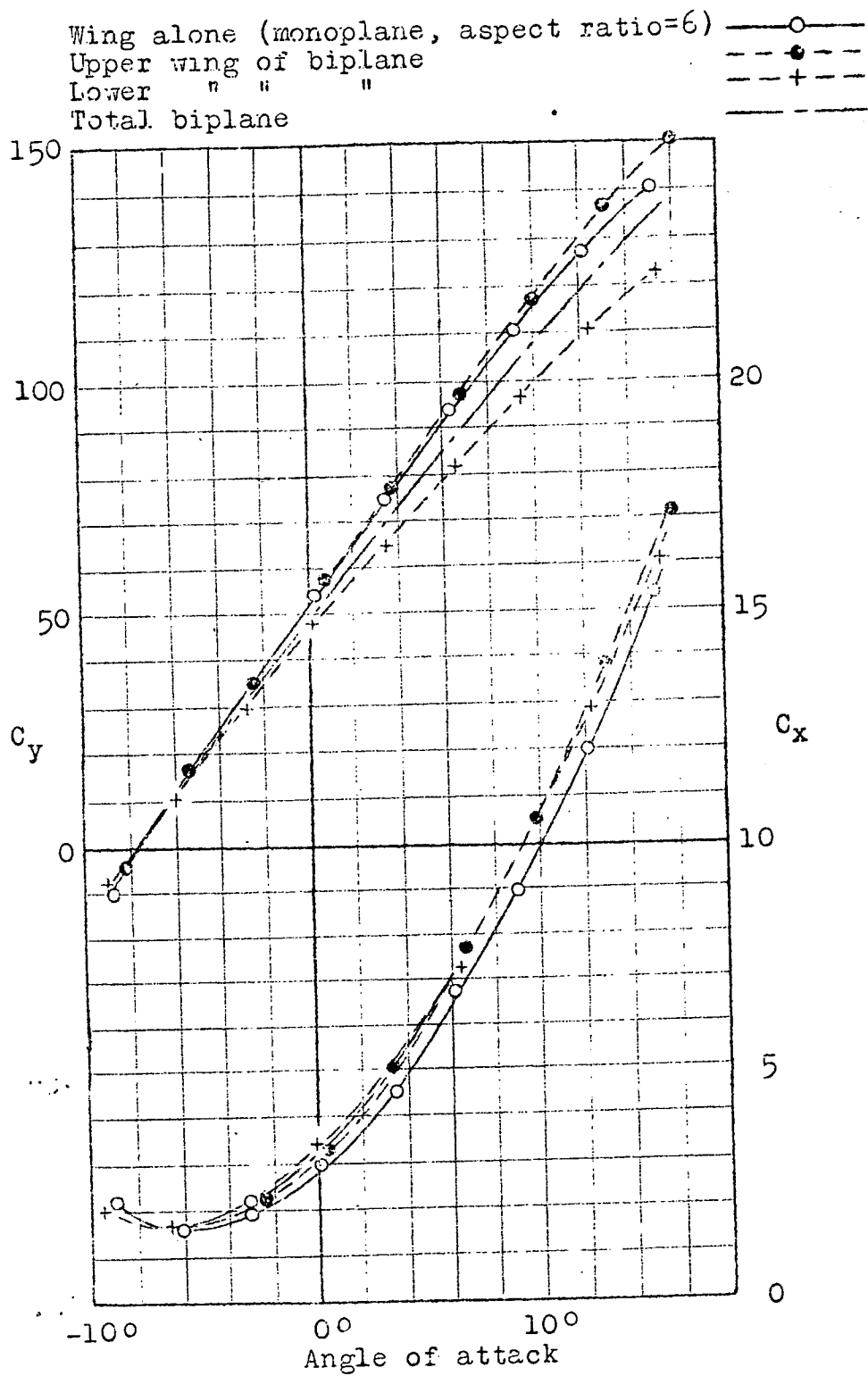


Fig. 4 Biplane S.C. 56c.a. Gap 187.0 mm(7.36 in.)  
 $b/G=3.78$

Fig. 5

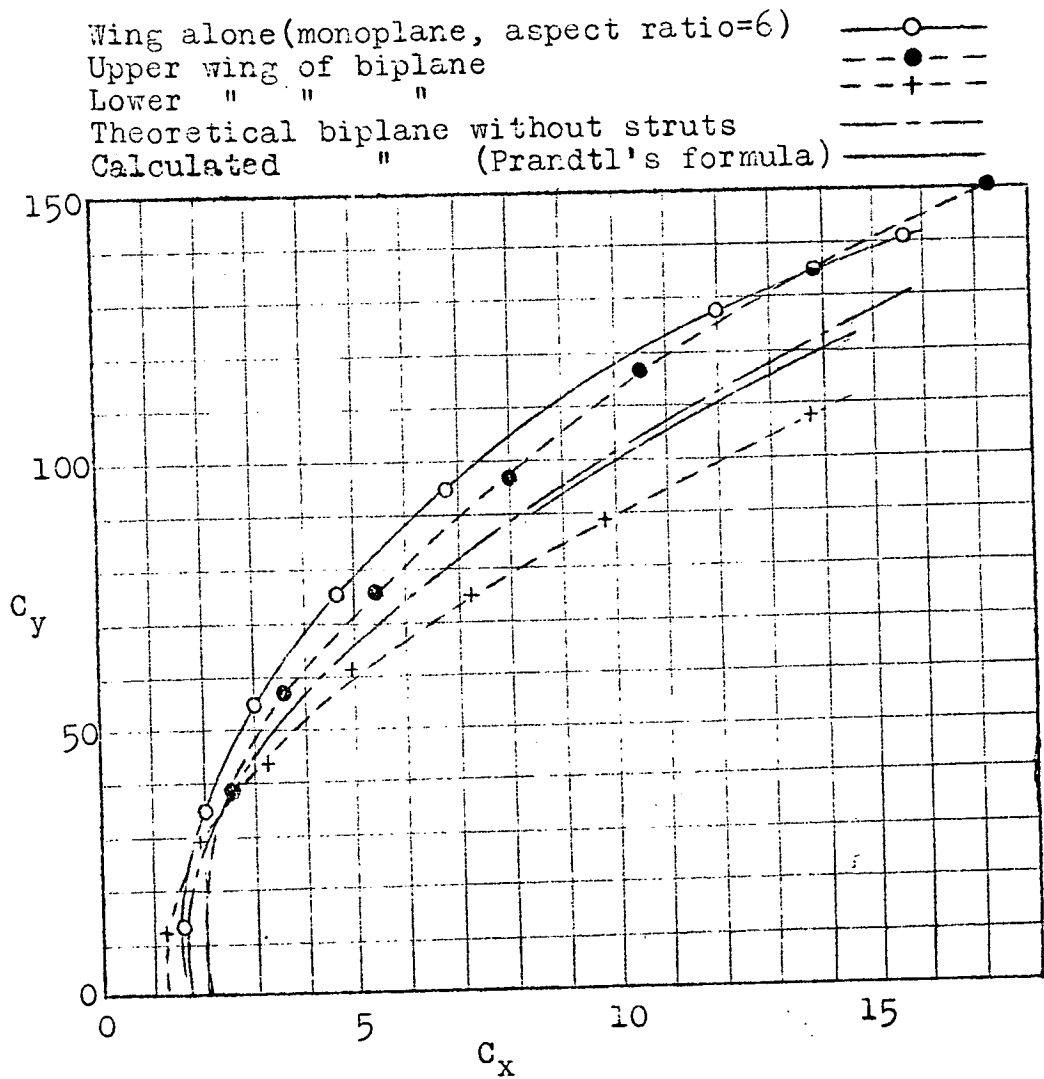


Fig. 5 Biplane S.C. 56c.a. Gap 135 mm (5.31 in.)  
 $b/G=5.25$

Fig. 6

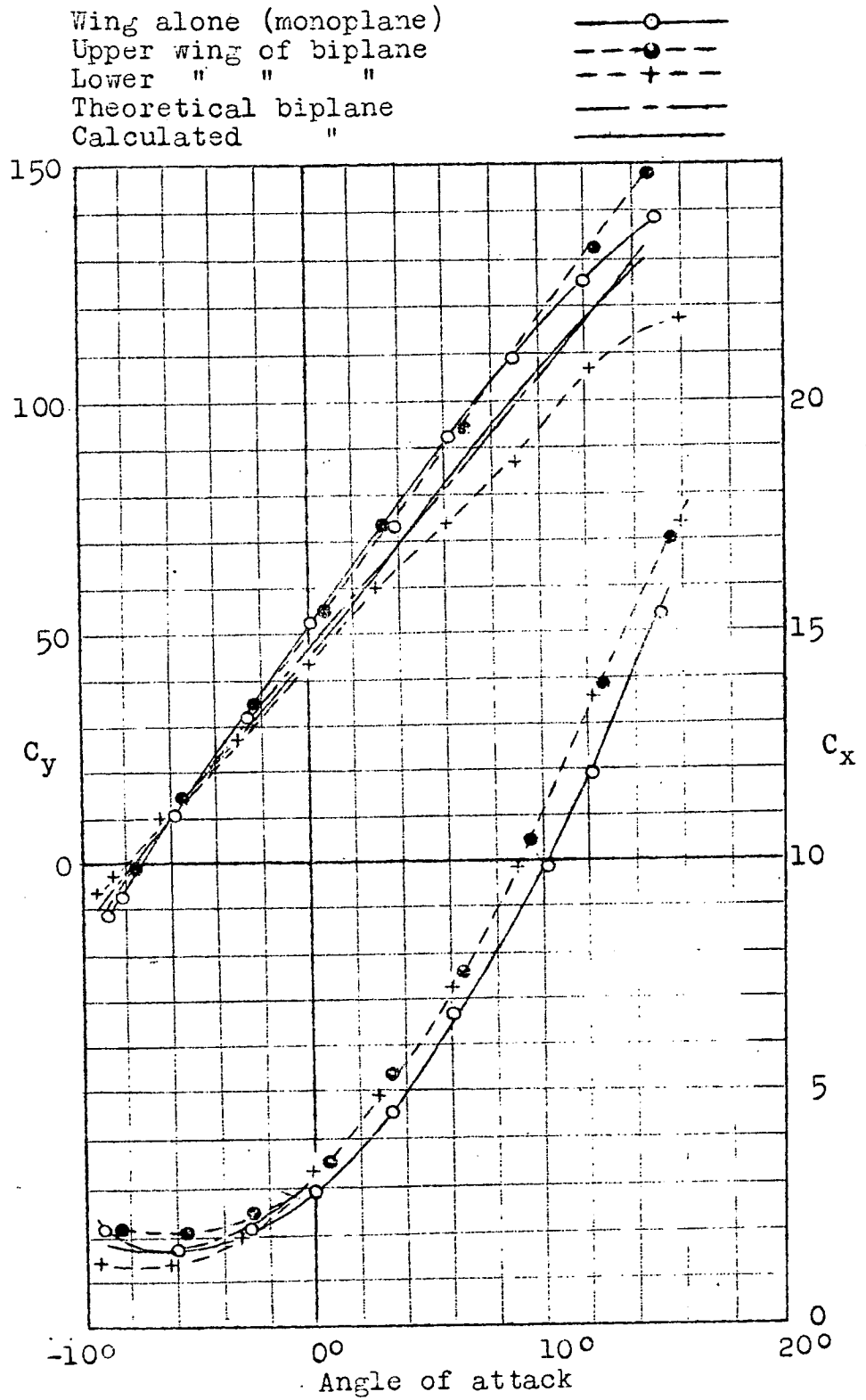


Fig. 6 Biplane S.C. 56c.a. Gap 135.0 mm (5.31 in.)  
 $b/G=5.25$

Fig. 7

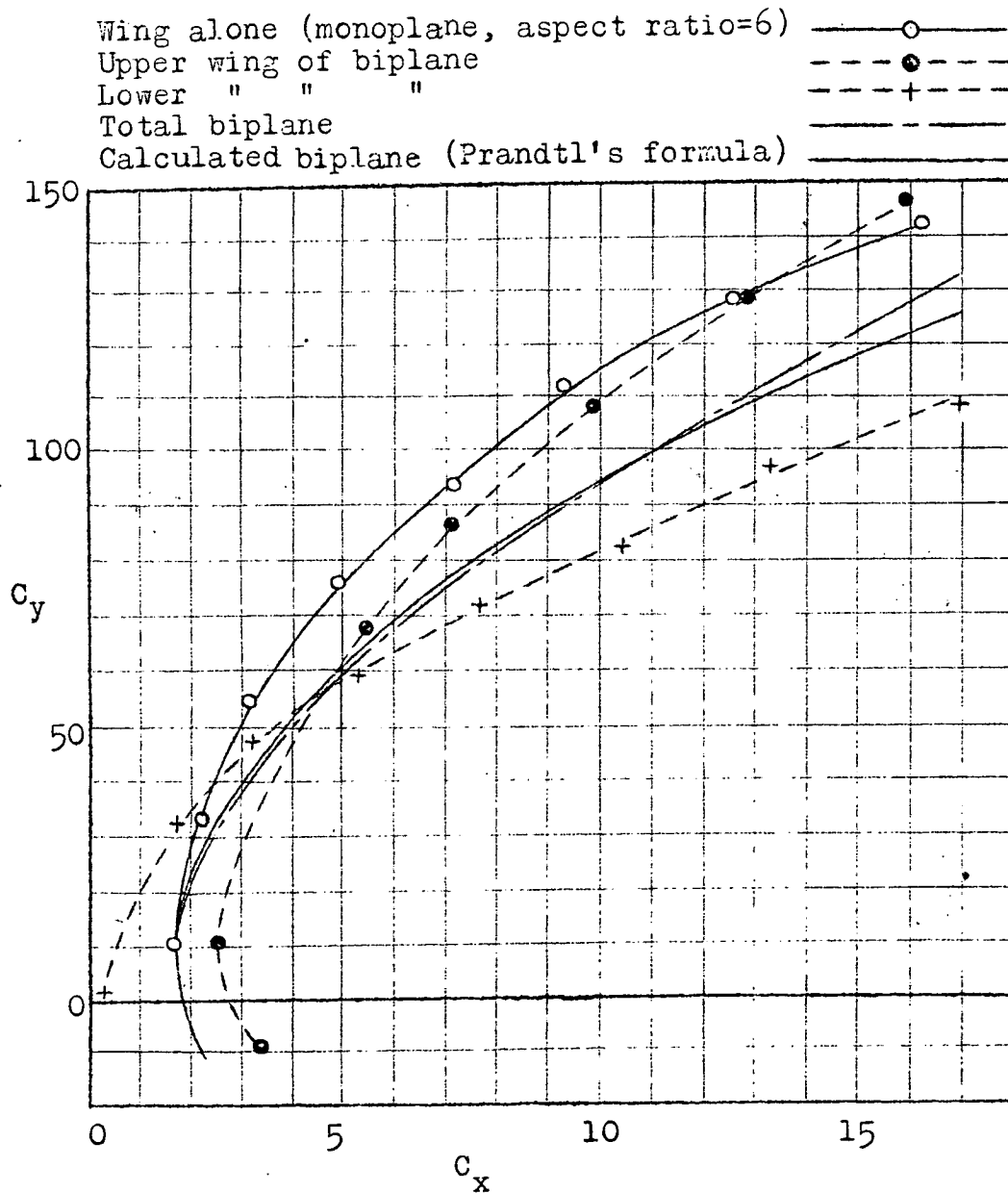


Fig. 7 Biplane S.C. 56c.a. Gap 87.5 mm (3.44 in.)  
 $b/G=8.1$

Fig. 8

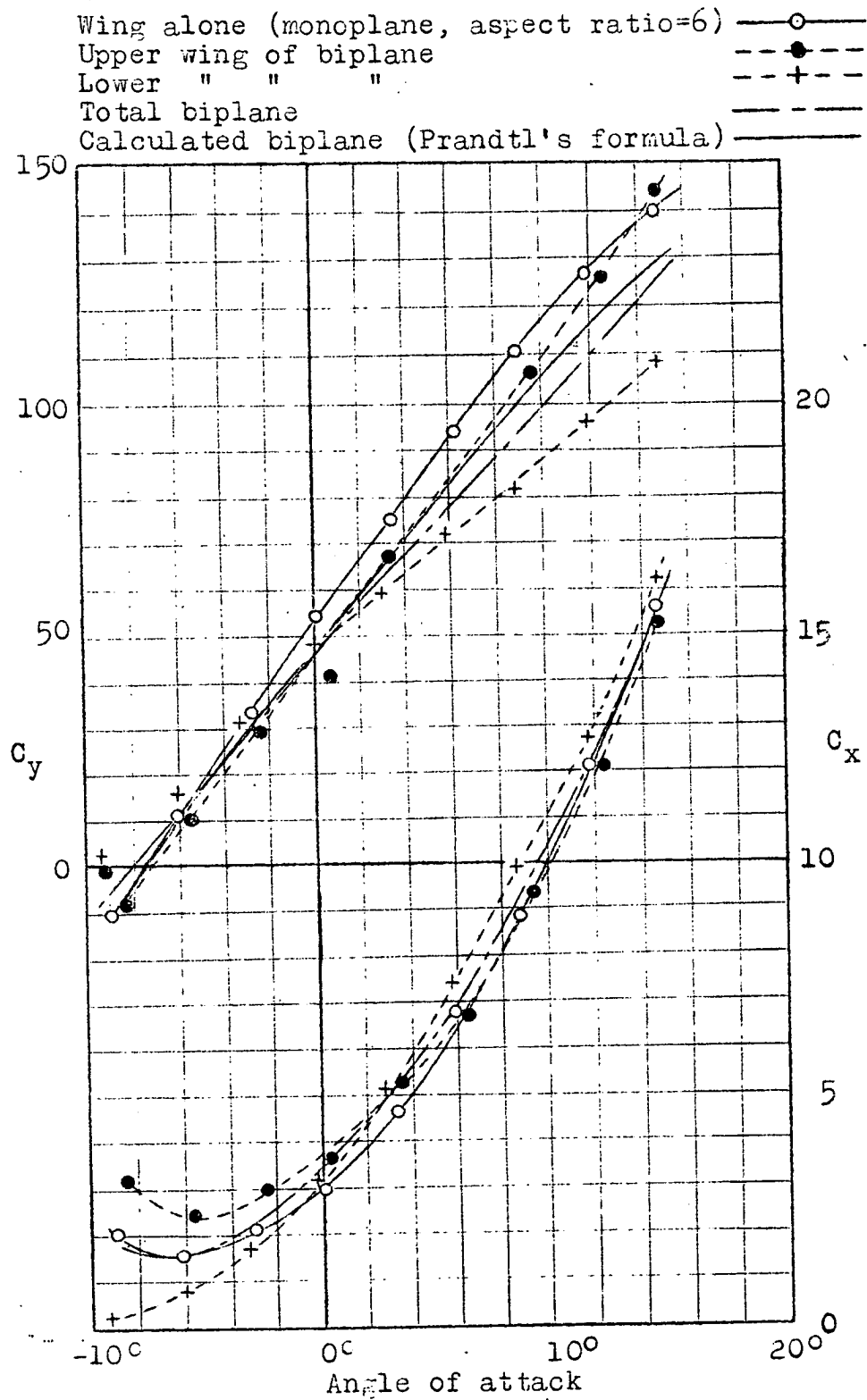


Fig. 8 Biplane S.C. 56c.a. Gap 87.5 mm (3.44 in.)  
 $b/G=8.1$



Fig. 9

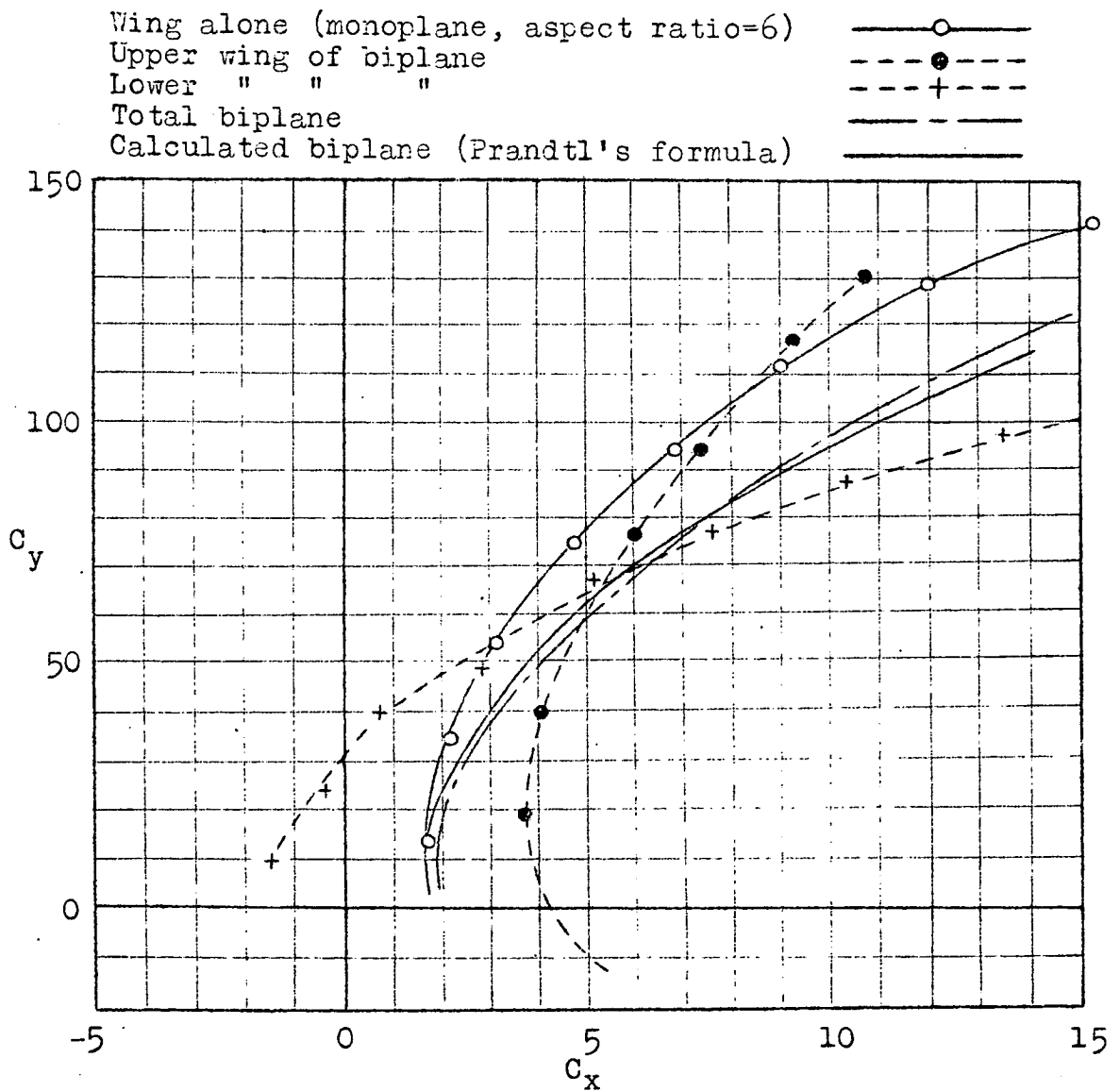


Fig. 9 Biplane S.C. 56c.a. Gap 60.0 mm (2.36 in.)  
 $b/G=118.0$

Fig. 10

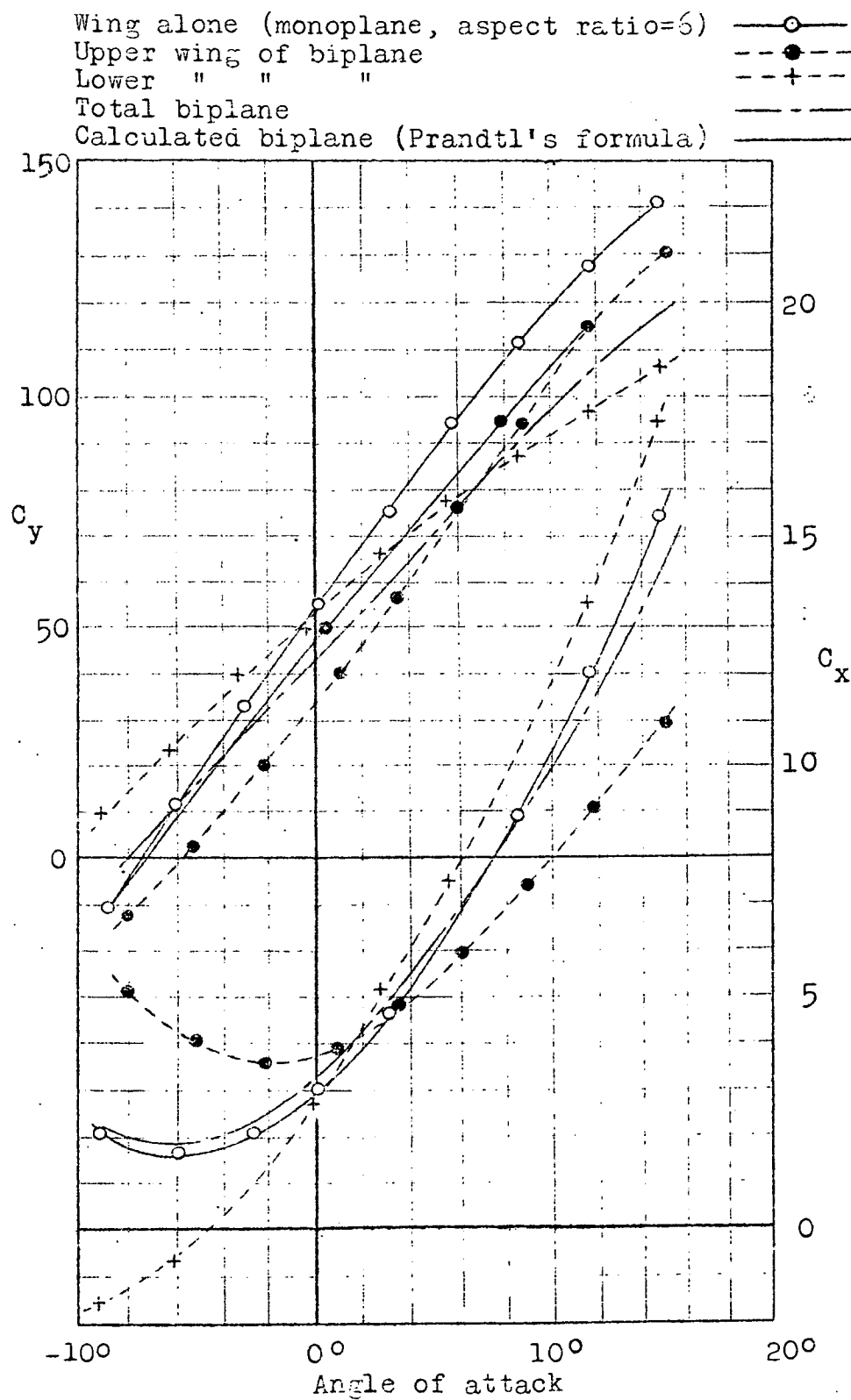
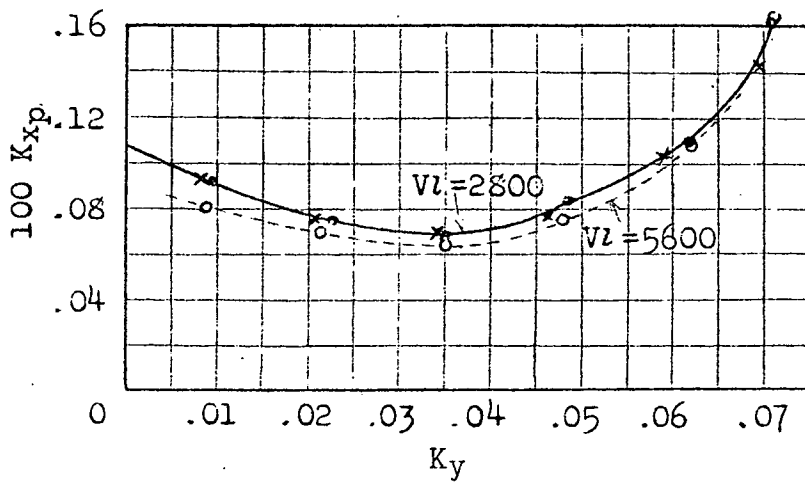
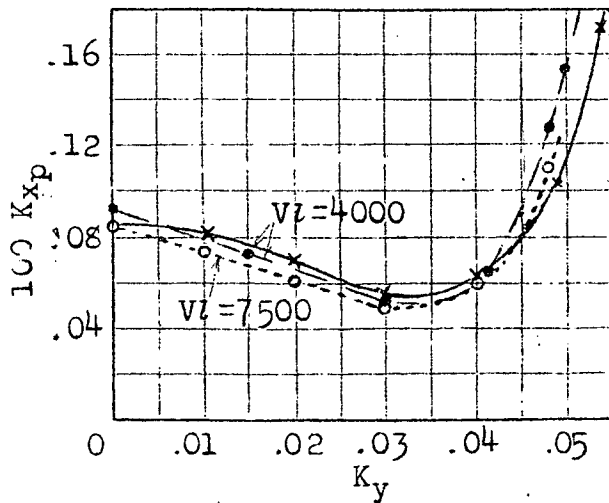
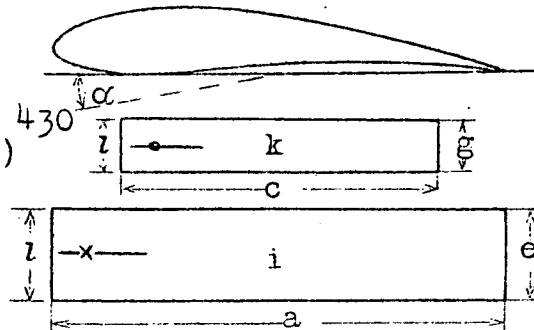


Fig. 10 Biplane S.C. 56c.a. Gap 60.0 mm (2.36 in.)  
 $b/G=11.8$



Gottingen 430  
(E. 356)



$a = 1000$  mm (39.37 in.)

$b = 800$  " (31.50 " )

$c = 708$  " (27.90 " )

$d = 290$  " (11.42 " )

$e = 200$  " ( 7.87 " )

$f = 145$  " ( 5.71 " )

$g = 118$  " ( 4.65 " )

$h$ ,  $\{S = .232 \text{ m}^2 (2.50 \text{ sq.ft.})$   
 $\{V = 14 \text{ m/s (45.9 ft./sec.)}$

$i$ ,  $\{S = .200 \text{ m}^2 (2.15 \text{ sq.ft.})$   
 $\{V = 14 \text{ m/s (45.9 ft./sec.)}$

$j$ ,  $\{S = .116 \text{ m}^2 (1.25 \text{ sq.ft.})$   
 $\{V = 28 \text{ m/s (91.9 ft./sec.)}$

$k$ ,  $\{S = .083 \text{ m}^2 ( .89 \text{ sq.ft.})$   
 $\{V = 26 \text{ m/s (83.3 ft./sec.)}$

$l = \text{Chord}$

Besson  
(E. 352)

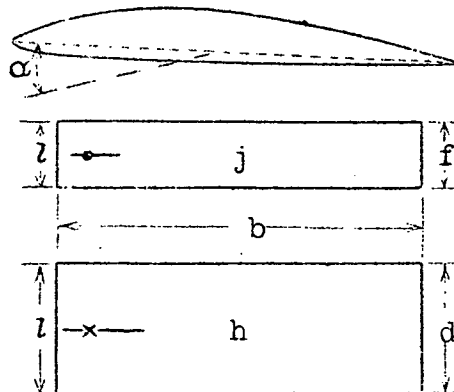


Fig.11 Drag on similar wing sections with different chords

Fig. 12

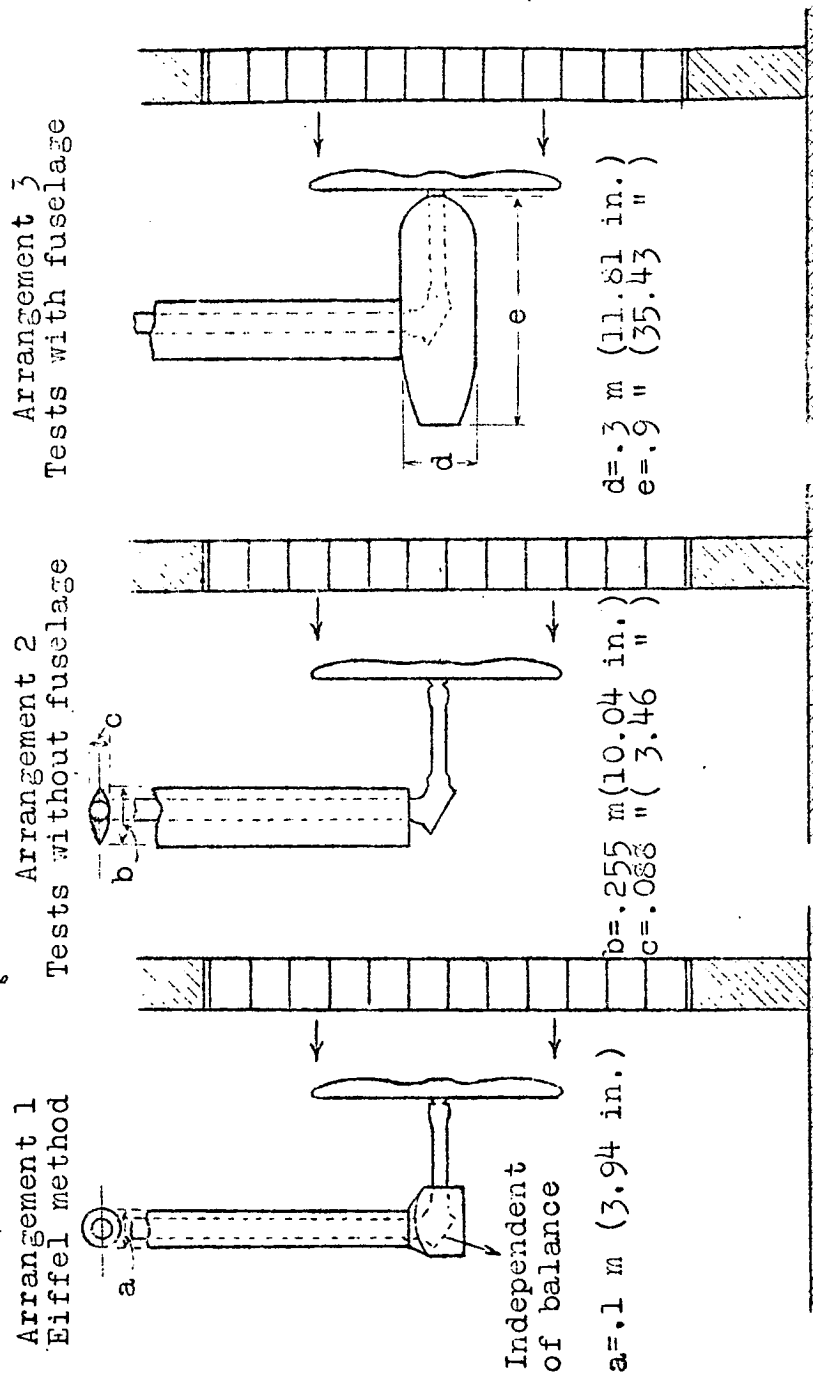


Fig. 12 Effect of presence of fuselage in propeller tests.

Fig.13 a

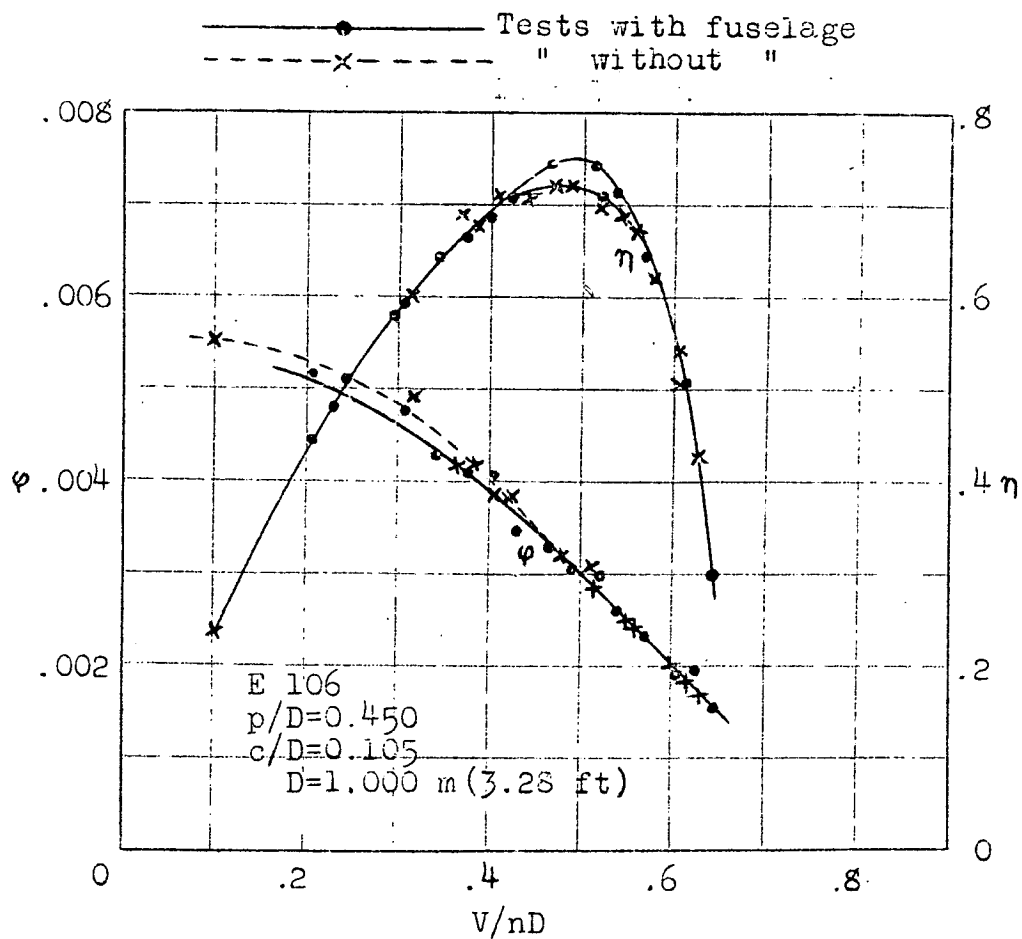
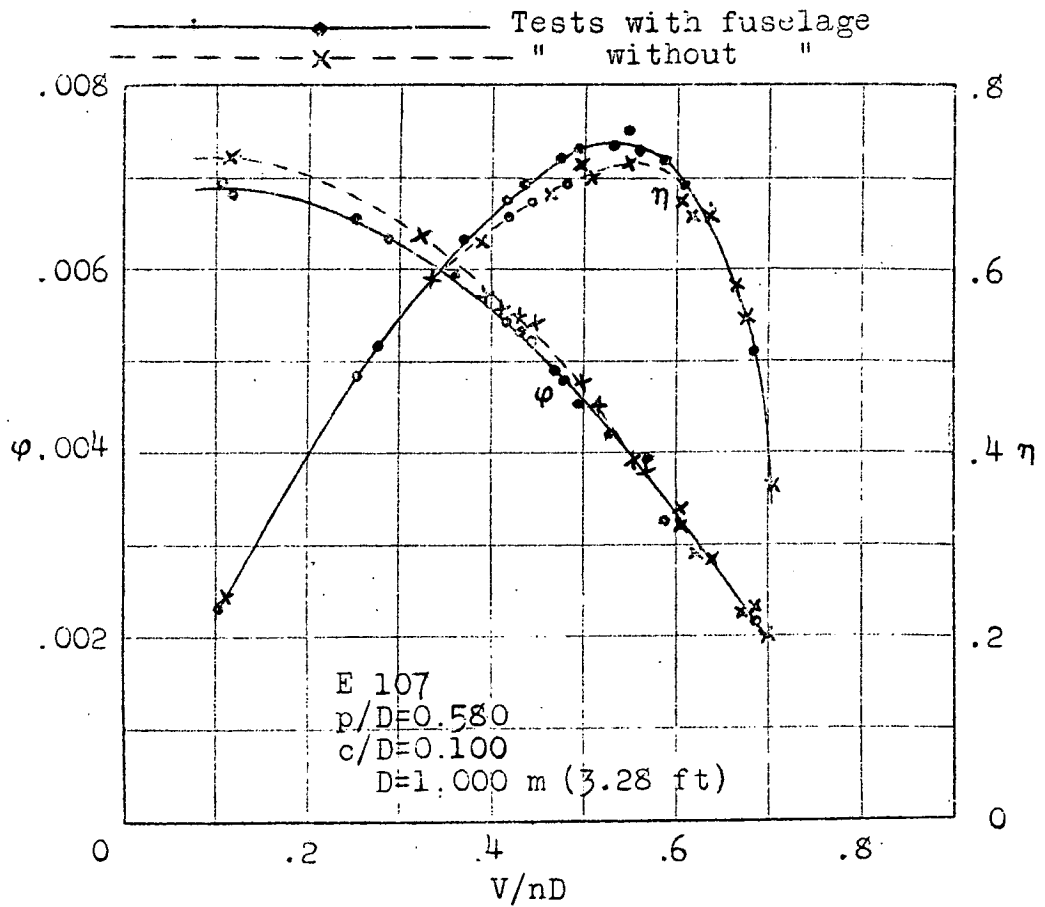


Fig.13 Effect of presence of fuselage in propeller tests.

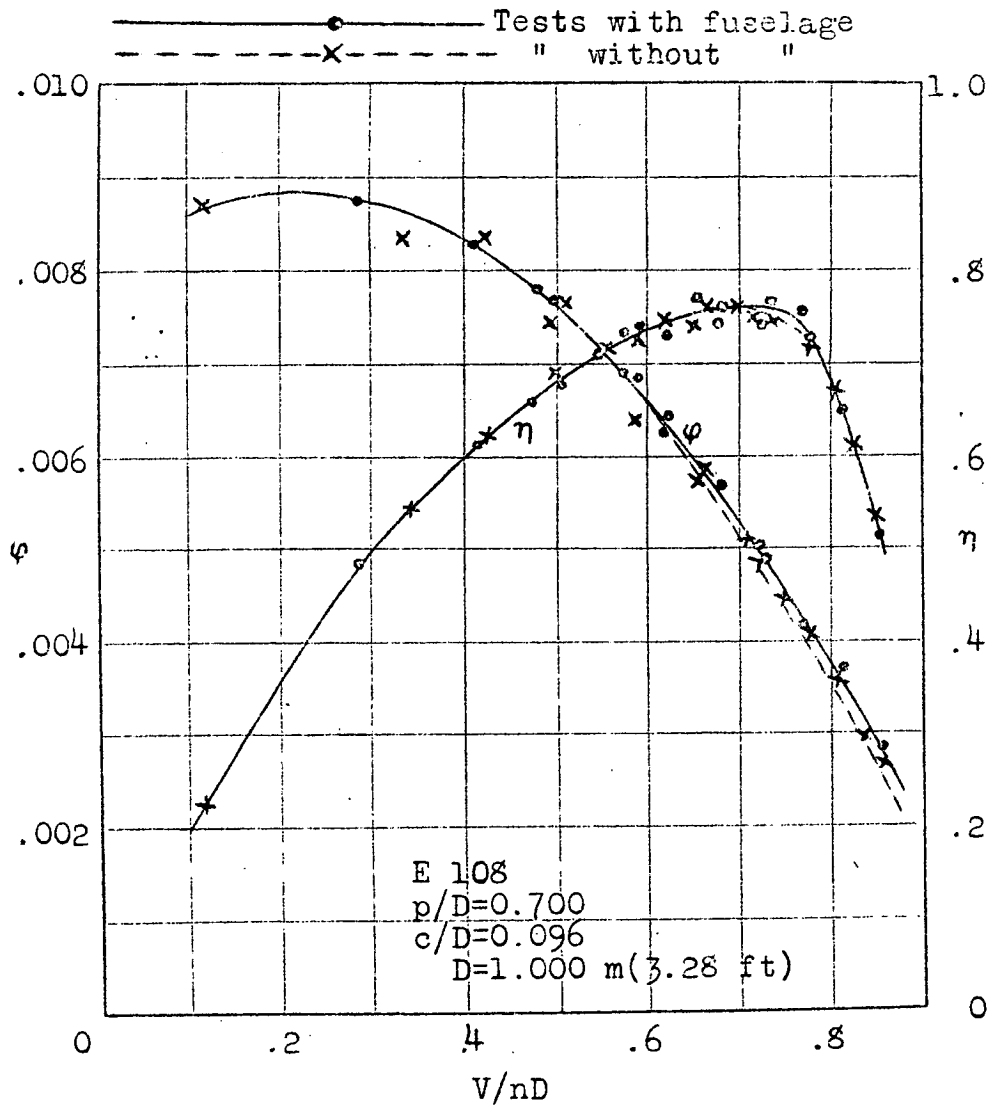
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Fig.13 b



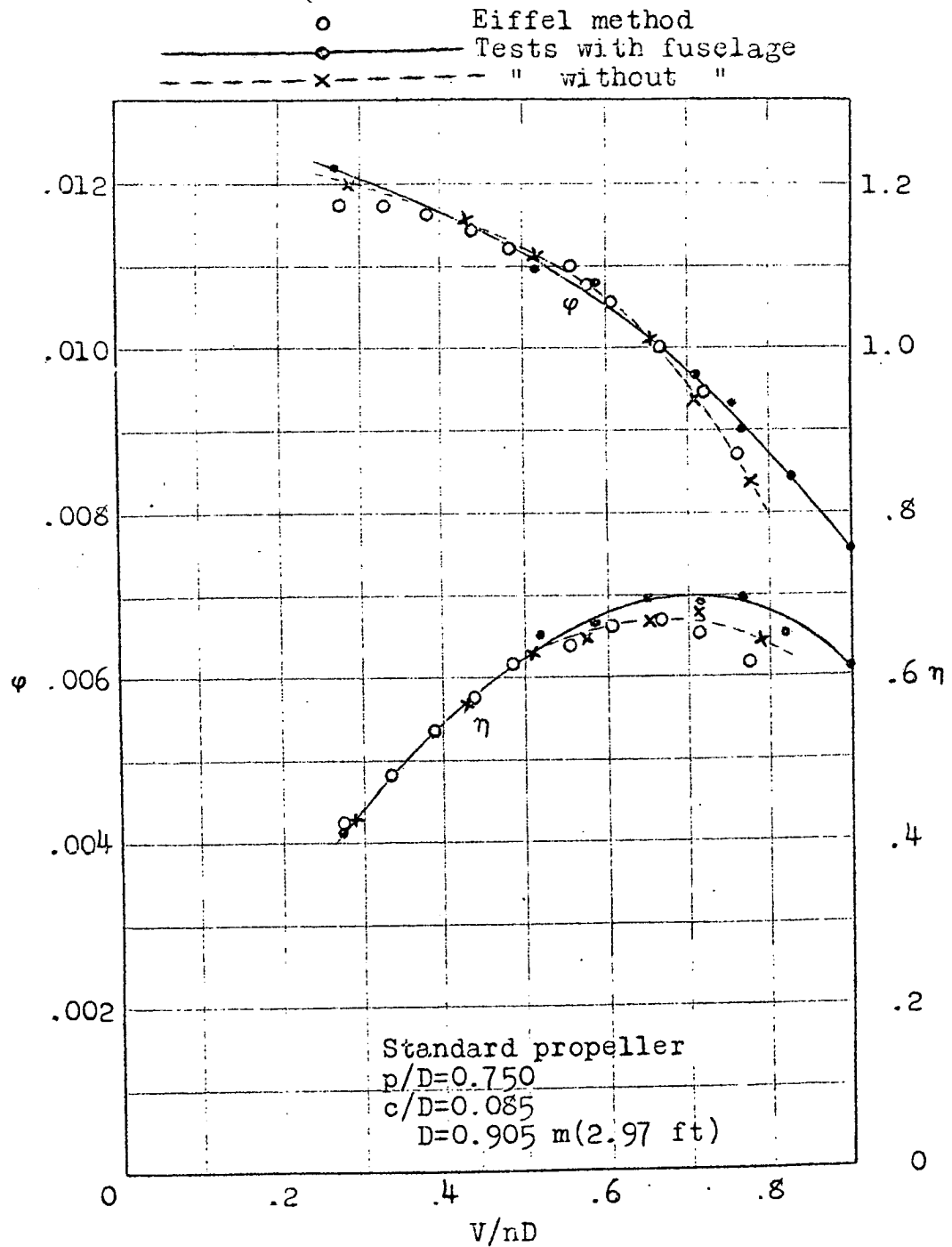
Continuation of Fig.13

Fig.13 c



Continuation of Fig.13

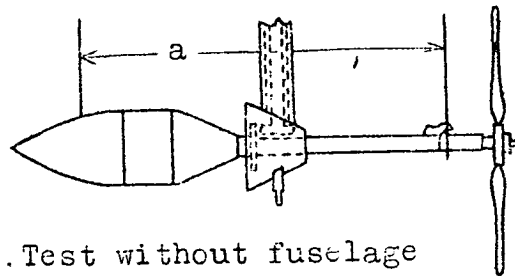
Fig.13 d



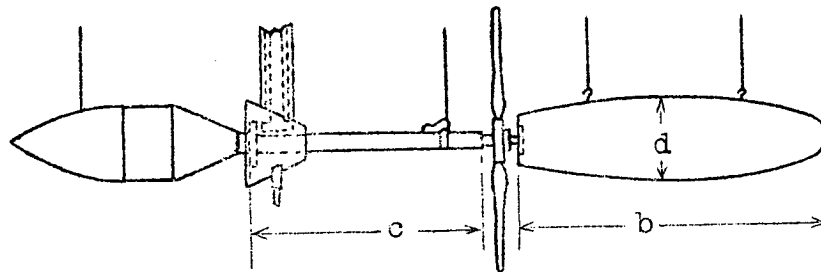
Continuation of Fig.13



Fig. 14



I. Test without fuselage



II. Test with fuselage

$a = 1230 \text{ mm (48.42 in.)}$   
 $b = 1040 \text{ " (40.94 " )}$   
 $c = 785 \text{ " (30.91 " )}$   
 $d = 290 \text{ " (11.42 " )}$

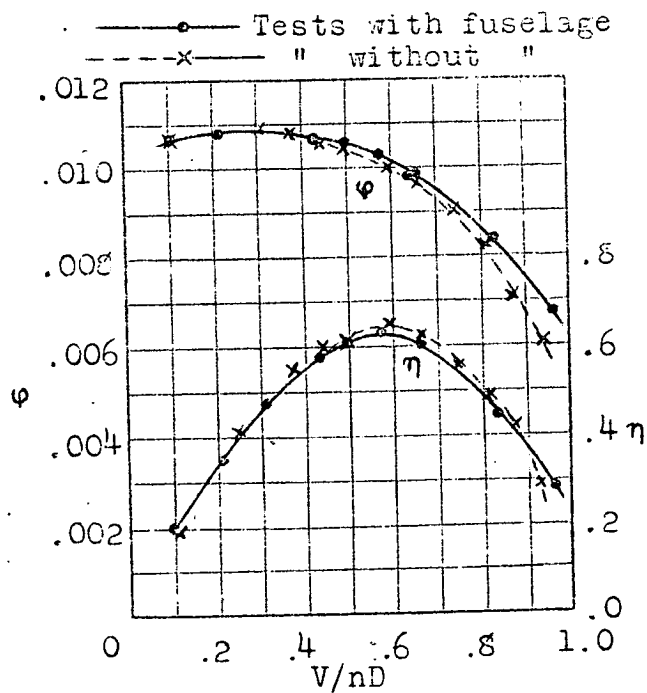
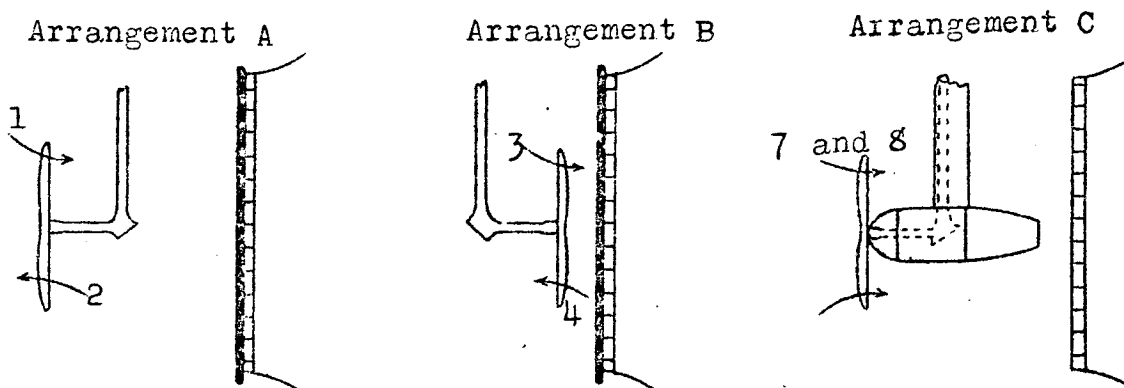


Fig. 14 Effect of presence of fuselage in propeller tests.

Fig. 15.



Experiment	$\tau$	$\varphi$	$q$	Remarks
Arrangement A {1	.0194	.0103	.2610	Prop. blows against closed doors
-ment A {2	.0200	.0103	.2750	" draws from " "
Arrangement B {3	.0197	.0100	.2750	Prop. blows against closed doors
-ment B {4	.0210	.0105	.2890	" draws from " "
Arrangement B {5	.0202	.0114	.2500	Prop. draws from doors opened 90°
-ment B {6	.0202	.0118	.2440	" " " " " " wide*
Arrangement C {7	.0187	.0101	.2540	Test without fuselage
-ment C {8	.0190	.0102	.2560	" with "

\* Turned clear back.

Fig 15. Testing helicopter propellers. Effect of presence of fuselage.